DRAINAGE CORRELATION RESEARCH PROJECT

For the

Montana State Highway Commission

ENGINEERING

Research Laboratories

MONTANA STATE UNIVERSITY, BOZEMAN

FINAL REPORT

DRAINAGE CORRELATION RESEARCH PROJECT

For the

Montana State Highway Commission
Planning Survey Section

In cooperation with the
U. S. Department of Transportation
Federal Highway Administration

By

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The opinions, findings and conclusions expressed in this publication are those of the author and not necessarily those of the Federal Highway Administration and the Montana State Highway Commission.

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CHAPTER I

INTRODUCTION

An important problem in highway design is that of determining flow capacities required for drainage structures. Although the problem exists for structures of all sizes, there is a particular shortage of design criteria for small structures such as culverts. Culvert installations ordinarily are used where the discharge originates from small watersheds of a few acres or a few square miles. The determination of peak discharge magnitudes and corresponding return frequency intervals is essential to economical engineering design.

Until the year 1955 there was very little reliable information available regarding peak discharge magnitudes and frequencies from small drainage areas in Montana. In that year the U.S. Geological Survey instituted a Small-Area Peak-Flow Highway program in cooperation with the Montana State Highway Commission. The cooperative program involves the determination of peak flow rates at selected stations on small watersheds. Measurements were begun at 45 crest stage gaging stations in 1955, with more stations being added in 1959 and later years, with 228 stations being in operation in 1969.

In order to derive the maximum possible utility and benefit from the cooperative program a comprehensive study of peak flows from small watersheds (1 to 100 square miles) in Montana was undertaken by Montana State University in 1963. Principal objectives of the study were to obtain information which would at least partially answer the following questions:

1. Can existing precipitation and climatological data be used to predict the frequency of flood magnitudes on small watersheds in Montana.

2. Do comprehensive studies of a few of the watersheds in the peak-flow study of the U.S. Geological Survey (i.e., detailed precipitation and snow measurements, soil types, topography, land use, continuous flow measurements, etc.) yield data which extend the usefulness of the results obtained from the peak flow determinations being made by the Geological Survey.

3. What frequency of flood can be safely predicted from short-term peak flow records. What length of records should be made by the Geological Survey to safely predict floods of given frequencies.

In the furtherance of the Project objectives, the study was initially divided into two phases:

1 - Precipitation data gathered by the U.S. Weather Bureau (ESSA) were assembled and studied to determine what correlation exists between such data and peak flows from small watersheds. In this phase data already available or being obtained by others were utilized.

2 - Comprehensive hydrologic studies of four of the U.S. Geological Survey watersheds were made. Data obtained were correlated with the results of the Geological Survey program. In this phase new data were gathered specifically for this Project.

As the investigation progressed, the scope of the Project was enlarged to include a study of various methods currently in use by other agencies for the

prediction of peak flows and frequencies, and this led to a critical assessment of all modern hydrologic techniques and their applicability to Montana.

The various phases of the investigation are reported in separate chapters of this report. Reference is frequently made to the one preliminary report and seven interim reports which have been prepared and submitted during the life of the Project. Although it is intended that this final report be complete and self-contained, many details which appeared in the earlier reports are only briefly summarized herein.

A review of modern hydrologic techniques appears in Appendix A.

Several graduate students and a large number of undergraduate students at Montana State University were employed at various times on this Project. The conscientious efforts of these individuals should be acknowledged. Faculty colleagues, Dr. E. R. Dodge of the Department of Civil Engineering and Engineering Mechanics, Dr. T. L. Hanson of the Department of Agricultural Engineering, and Dr. K. J. Tiahrt of the Department of Mathematics served as technical consultants on the Project, and each contributed immeasurably to the study. Professor A. C. Scheer of the Department of Civil Engineering and Engineering Mechanics was Project Coordinator, and advised on fiscal and administrative matters. Dr. Paul Brown, Agricultural Research Service, USDA, obtained the loan of an Infiltrometer. Technical personnel from the U.S. Geological Survey, ESSA, and Soil Conservation Service were consulted freely, and without exception they were most cooperative. A total of 18 ranchers in eastern Montana not only permitted the installation of meteorological instruments on their property, but serviced the equipment regularly and mailed in charts and records faithfully each month. Finally mention should be made of the Montana Highway Commission

and U.S. Federal Highway Administration personnel, both in Helena and at District offices throughout the state, who aided the Project in countless respects.

CHAPTER II

PRECIPITATION-STREAMFLOW CORRELATIONS

Phase I of the Proposal for this Project envisioned the compilation and study of precipitation data gathered by the U.S. Weather Bureau (now the Environmental Science Services Administration) to determine what correlation exists between these data and peak flows on small watersheds. This chapter describes the procedures that have been followed in pursuance of this objective.

ESSA operates nearly 350 precipitation measurement stations in Montana of which about 90 are equipped with continuous-recording weighing raingages. More than 100 of the stations have been in operation at least 50 years. No significant amount of precipitation data, except for that at the ESSA stations, was discovered.

Interim Report #7 (Robinson and Williams, 1968) describes the development of a method to relate peak discharge to maximum rainfall intensity on small Montana watersheds. Although data available are not sufficient to adequately test the method, results obtained are encouraging. It is believed real possibilities exist for development of more rational culvert design procedures.

RAINFALL FREQUENCY - PEAK FLOW FREQUENCY METHOD

In relating frequency of rainfall intensity to frequency of peak flow it is first recognized that a peak flow which has a certain return period, (say ten years) may be produced by any one of numerous rainstorms. Depending upon a host of antecedent moisture factors, watershed characteristics and meteorological conditions, the ten year discharge might be produced by a

six-hour duration rainstorm of one-inch per hour intensity, by a three-hour duration rainstorm of two inches per hour intensity, or by a twelve-hour duration rainstorm of one-half inch per hour intensity. If soil conditions were right, the same ten year discharge could, in fact be produced by a six-hour duration rainstorm of one-half inch per hour intensity, or it might require a six-hour duration rainstorm of two inches per hour. In other words an infinite variety of rainstorms might, given the proper conditions, produce a peak discharge of ten years return period.

Although there would seem to be little possibility of a simple function relating 10 year peak flow to 10 year rainfall intensity (i.e. $Q_{10} = K \times I_{10}$) it could be hypothesized that at higher return periods such a relationship would become more valid. This is, a rainfall of such intensity that it occurs once in 50 years would be expected to produce a peak discharge having a return period close to 50 years; and even more extreme events might be expected to follow even more closely the function $Q_i = K \times I_i$.

The prediction equation which was developed is based upon the above hypothesis and is given by

$$Q_i = \frac{R_i \, D_i}{F_i} \bar{Q} \qquad (1)$$

where Q_i is the peak discharge of return period i

R_i is a rainfall intensity ratio, being the ratio of the i-year rainfall intensity of some given duration to the mean annual rainfall intensity of the same duration

D_i is a rainfall-discharge recurrence factor which expresses the relationship between the rainfall recurrence relation for specified duration and the recurrence relation of peak annual discharges.

F_i is a rain-snow baseflow interaction ratio which reflects the relative dependence or independence of the frequency curves of rainfall-induced flows and snowmelt-induced flows.

$\bar{Q}$ is the mean annual peak discharge rate of the stream.

The return period i was taken as 50 years in this study.

Determination of R_i

Precipitation data from 18 ESSA stations in eastern Montana with recording raingages and 26 stations with non-recording raingages were examined. Peak 24-hour intensity was found for each year for the non-recording stations, and peak one-hour, peak two-hour, peak three-hour, peak four-hour, peak six-hour, peak eight-hour, peak 12-hour, and peak 24-hour intensities were obtained for each year for the recording stations. These data were analyzed statistically (by Gumbel's technique) to determine intensities corresponding to 50-year and to 2.33-year return periods. The ratio of these two values, $I_{50}/\bar{I}$ was determined in each case, and called the rainfall intensity ratio, R_{50}.

It was found that for rainstorm duration greater than 12 hours, the values of R were remarkably consistent (see Interim Report #7, Figure 11, page 66). This led to the conclusion that R values could be obtained from non-recording station data and these values could be applied to watersheds having travel times in excess of 12 hours.

A map of Montana showing isoplethals of R_{50} was shown in Interim Report #7 (Figure 12, page 68). Since preparation of the report further work has been done on refinement of R values, and the map which is shown herein as Figure 1 is believed to more accurately define R_{50} in eastern Montana.

Determination of D_i

Values of the rainfall-discharge recurrence factor D_i were obtained for eleven watersheds in eastern Montana varying in area from 30 to 684 square miles, having continuous streamflow records varying from 11 to 36 years. In analyzing streamflow records from these watersheds only that portion of the streamflow assumed attributable to rainfall was used. Snowmelt-induced runoff was separated out of the hydrographs where necessary by studying characteristic shapes of those hydrographs which evidently were totally caused by snowmelt, and subtracting comparable flows from hydrographs which were partly rain-caused and partly snowmelt-induced. Baseflow was separated out of the hydrographs by assuming that the baseflow equalled the average of the recorded minimum daily discharges during the month in question. D_i was computed for each watershed from extreme value distribution theory, and is given by

$$D_i = \frac{1 + C_{vQ} \dfrac{1}{\sigma_{nQ}} (\ln i - \bar{Y}_{nQ})}{1 + C_{vI} \dfrac{1}{\sigma_{nI}} (\ln i - \bar{Y}_{nI})} \tag{2}$$

where C_v is coefficient of variation (standard deviation divided by the mean) for discharge peaks (Q) or maximum rainfall intensities (I).

σ_n and $\bar{y}_n$ are expected values of standard deviation and mean for the

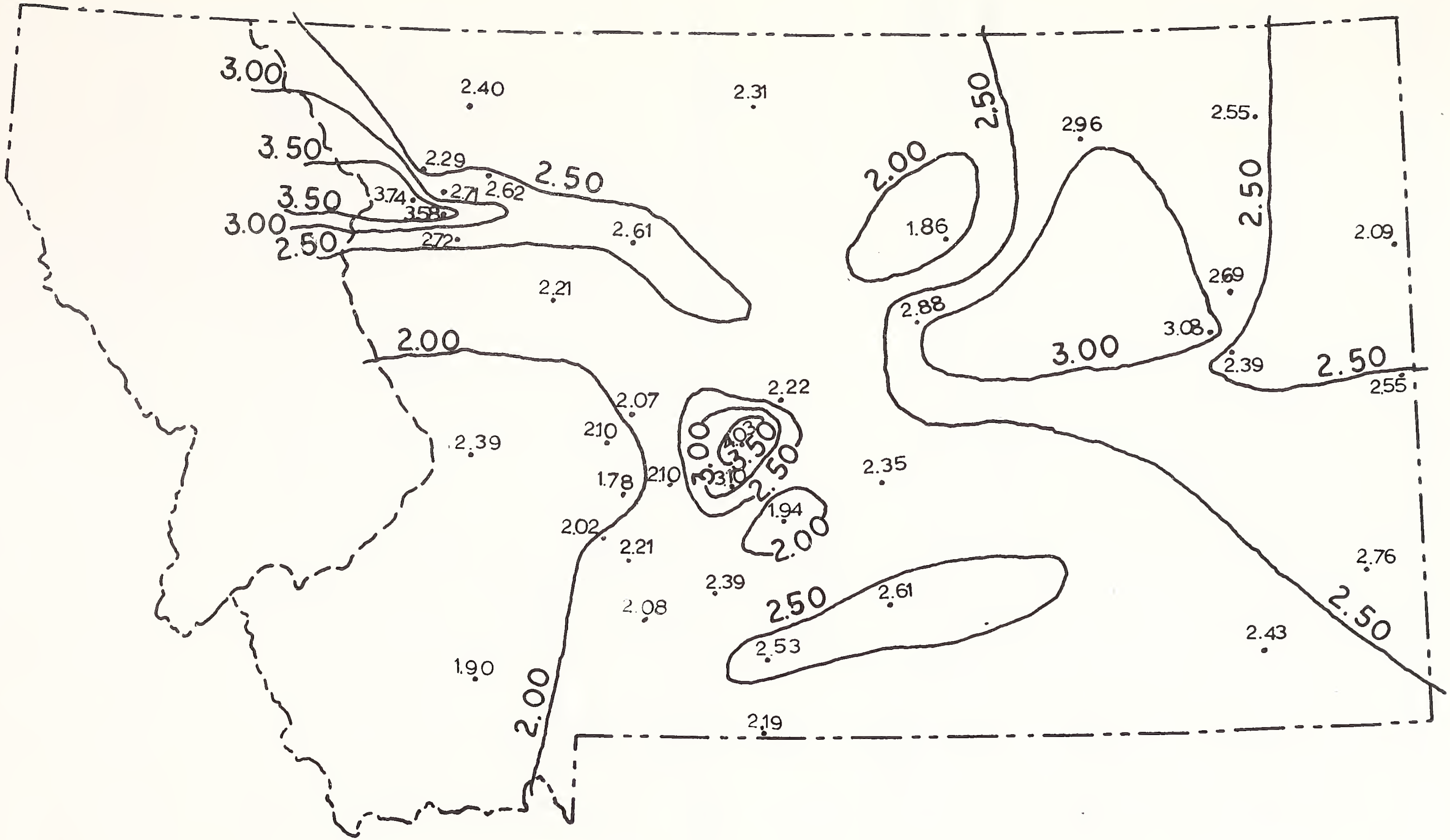


FIGURE 1 -- Isoplethals of the Rainfall Intensity, R_{50}, for Montana East of the Continental Divide

length of record of discharges (Q) or intensities (I).

i was taken as 50 years.

Isoplethals of D_{50} for the area of Montana east of the continental divide were shown in Interim Report #7 (Figure 13, page 70).

Determination of F_i

Values of the rain-snow baseflow interaction ratio, F_i, were computed for eleven watersheds (those used in determination of D_i, described above) from the relation

$$F_i = \frac{Q_R^i \;/\; \bar{Q}_R}{Q_T^i \;/\; \bar{Q}_T} \tag{3}$$

where Q_R^i and $\bar{Q}_R$ are peak discharge at i-year return period and mean annual discharge, due to rain only

Q_R^i and $\bar{Q}_R$ are peak discharge at i-year return period and mean annual discharge.

i was taken as 50 years.

Values of F_{50} were found to be quite erratic, and not apparently related to geographical or climatological factors. F_{50} was therefore tentatively taken as 1.45 (the average of the values obtained for the eleven watersheds).

TEST OF METHOD

A 50-year peak discharge was computed by the rainfall frequency-peak flow frequency method for each of 46 of the watersheds equipped with crest-stage gages. These peak discharges were compared to comparable values determined by the extreme value function (Gumbel method) and by the log-probability method. Results of the comparisons are shown in Figures 2 and 3. For most of the 46 watersheds the three methods predict very nearly the same discharge. On a few watersheds there is considerable discrepancy. In most of these cases the method developed herein gives smaller discharges than either of the methods used for checking.

DISCUSSION OF RESULTS

There is, of course, no final means of evaluating the rainfall frequency-peak flow frequency method (or any other method for that matter) because no values are available for comparison. This method has one important advantage over other methods, in that it is less sensitive to length of streamflow record. Streamflow records are used only to obtain mean annual discharge. The variance from the mean is obtained from precipitation records which are usually much longer than the streamflow records. A disadvantage is that each of the three parameters R, D and F must be developed separately for each recurrence frequency desired. R_{25} for instance is different from R_{50} and one cannot be computed from the other.

Interim Report #7 (Robinson and Williams, 1968) describing the rainfall frequency-peak flow frequency method was reviewed by D. C. Woo, for the Structural and Applied Mechanics Division, Federal Highway Administration. The following comments are intended to partially answer some of the questions raised by Woo.

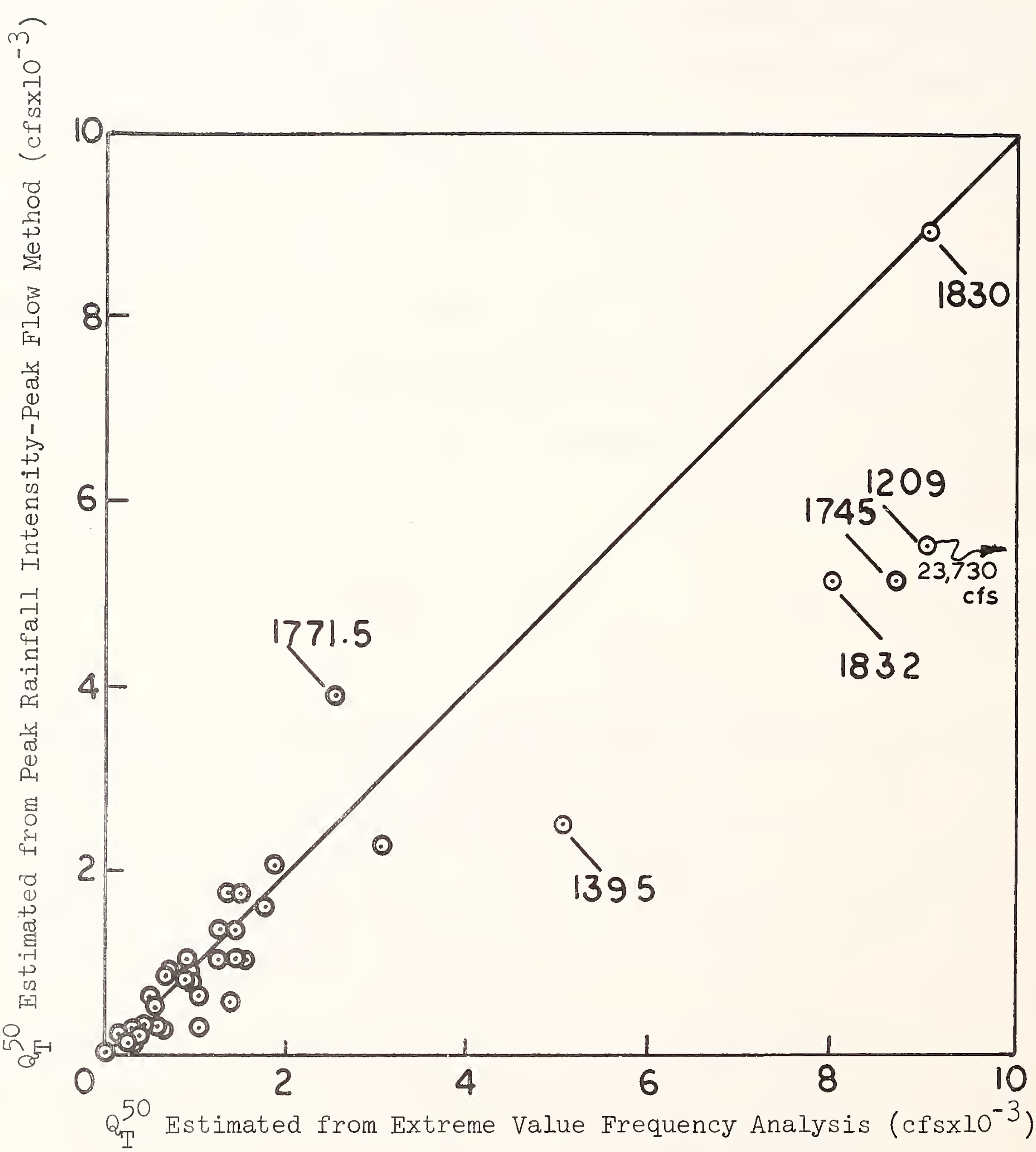


FIGURE 2. Comparison of estimates of Q_T^{50} between the peak rainfall intensity-peak flow method and extreme value frequency analysis.

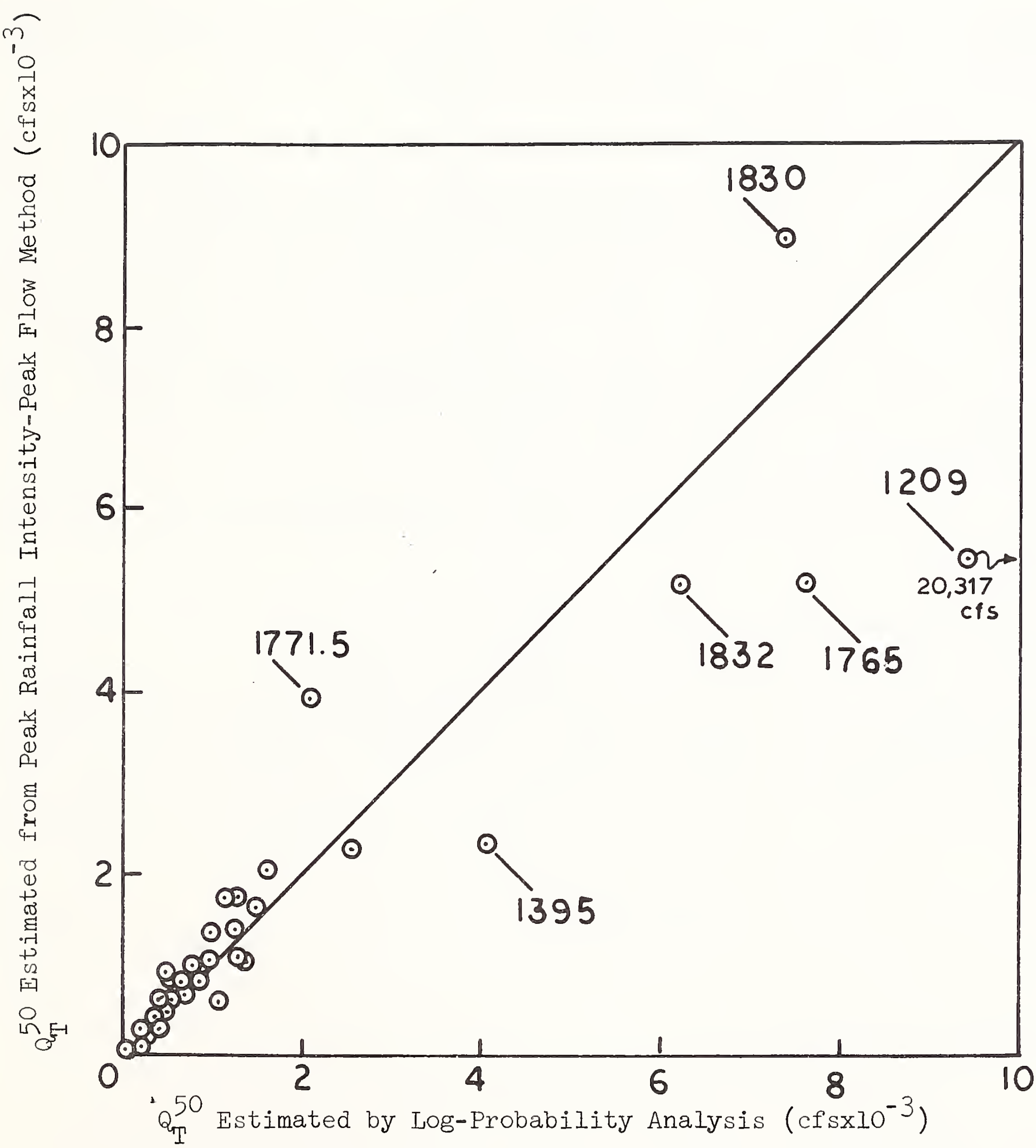


FIGURE 3. Comparison of estimates of Q_T^{50} between the peak rainfall intensity-peak flow method and log-probability analysis.

1. Woo wondered whether the extreme value distribution (Gumbel's technique) can properly be applied to rainfall intensities in Montana. (Gumbel's technique was used to determine precipitation intensities having a 50-year return period, and hence to determine values of $R_i = R_{50}/\bar{R}$.) Confidence curves have been drawn for the 24-hour precipitation intensities at 13 of the stations used in the study and also for the one-hour, two-hour, three-hour, four-hour, six-hour, eight-hour, 12-hour and 24-hour precipitation intensities at Martinsdale. These curves have been plotted on the Gumbel frequency graphs for these stations and are shown in Figures 4 to 24. The confidence curves show the range of return periods within which a given magnitude of the precipitation intensity may be expected with a probability of about 2/3.

Figures 4 to 24 also show 90 percent confidence bounds on the mean annual precipitation intensity, using the assumption that the population of rainfall intensities is a normal distribution, and calculated by Student's t,

$$t = \frac{(\bar{x} - \mu)\sqrt{n}}{S} \qquad (4)$$

where t is Student's t

(two-tailed test, 90% probability used)

$\bar{x}$ = sample mean

μ = population mean

S = sample standard deviation

n = number years record

Also shown on Figures 4 to 24 are 90 percent confidence upper bounds on the 50-year precipitation intensity, calculated by again assuming that

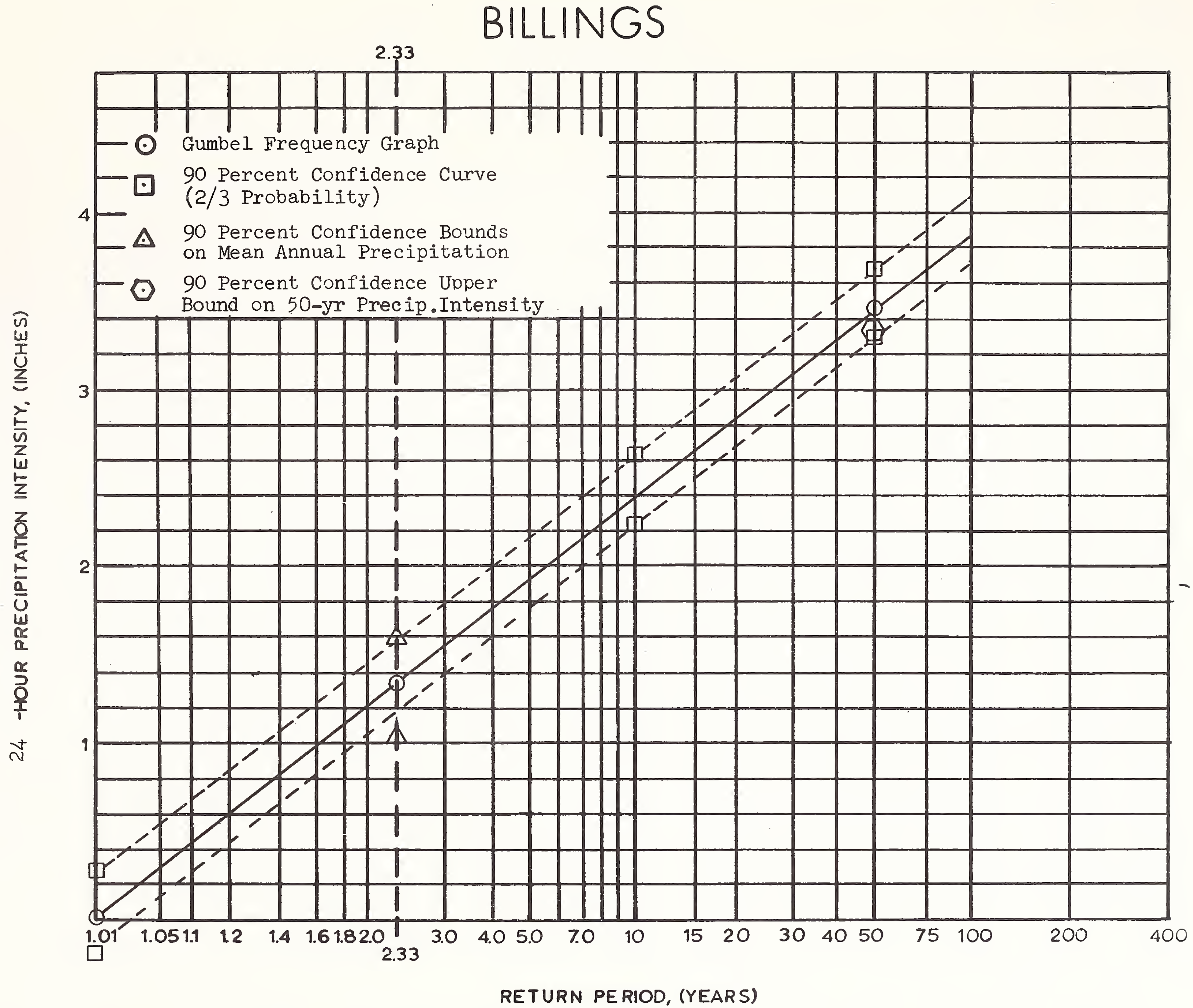


FIGURE 4 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Billings

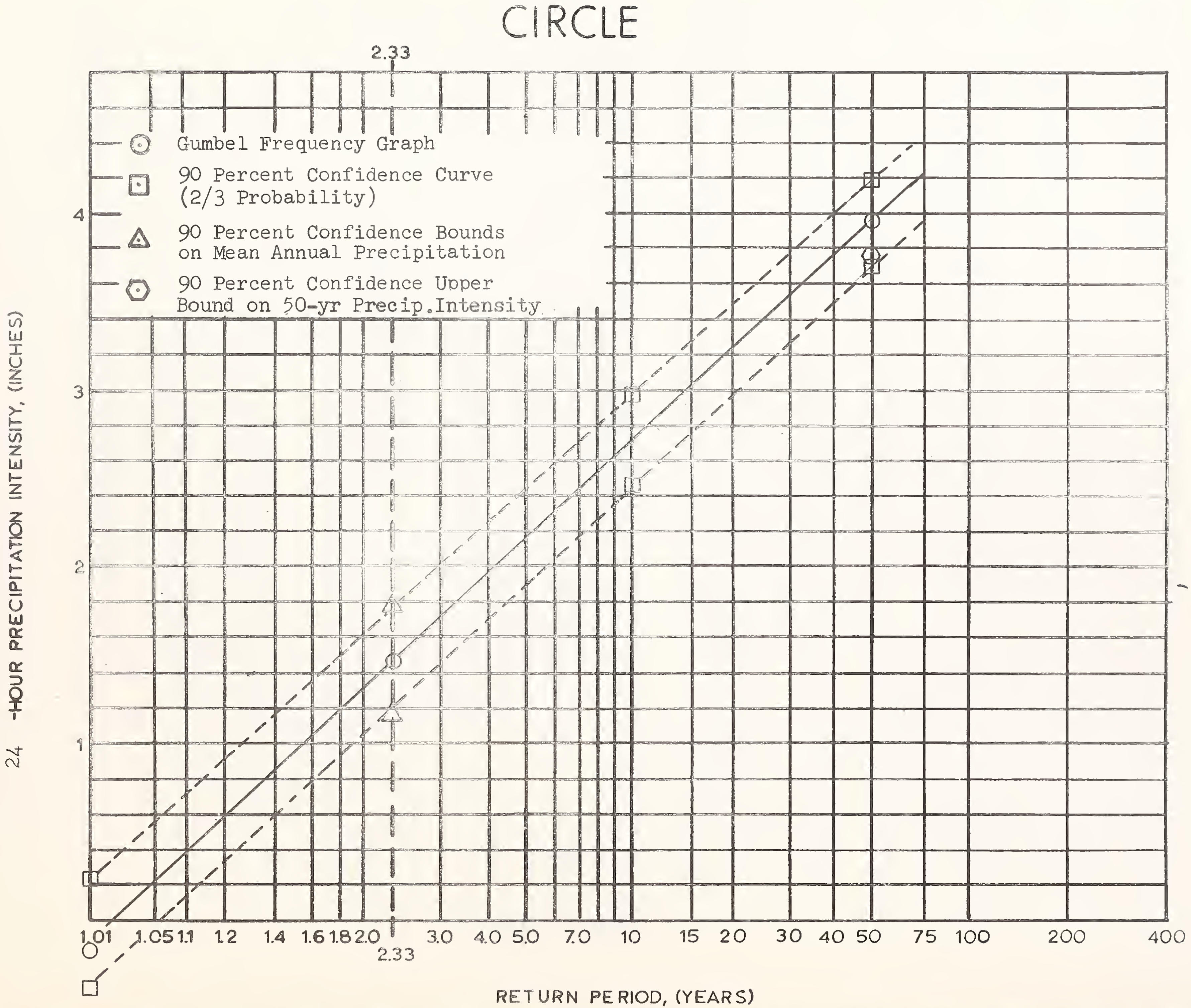


FIGURE 5 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Circle

EKALAKA

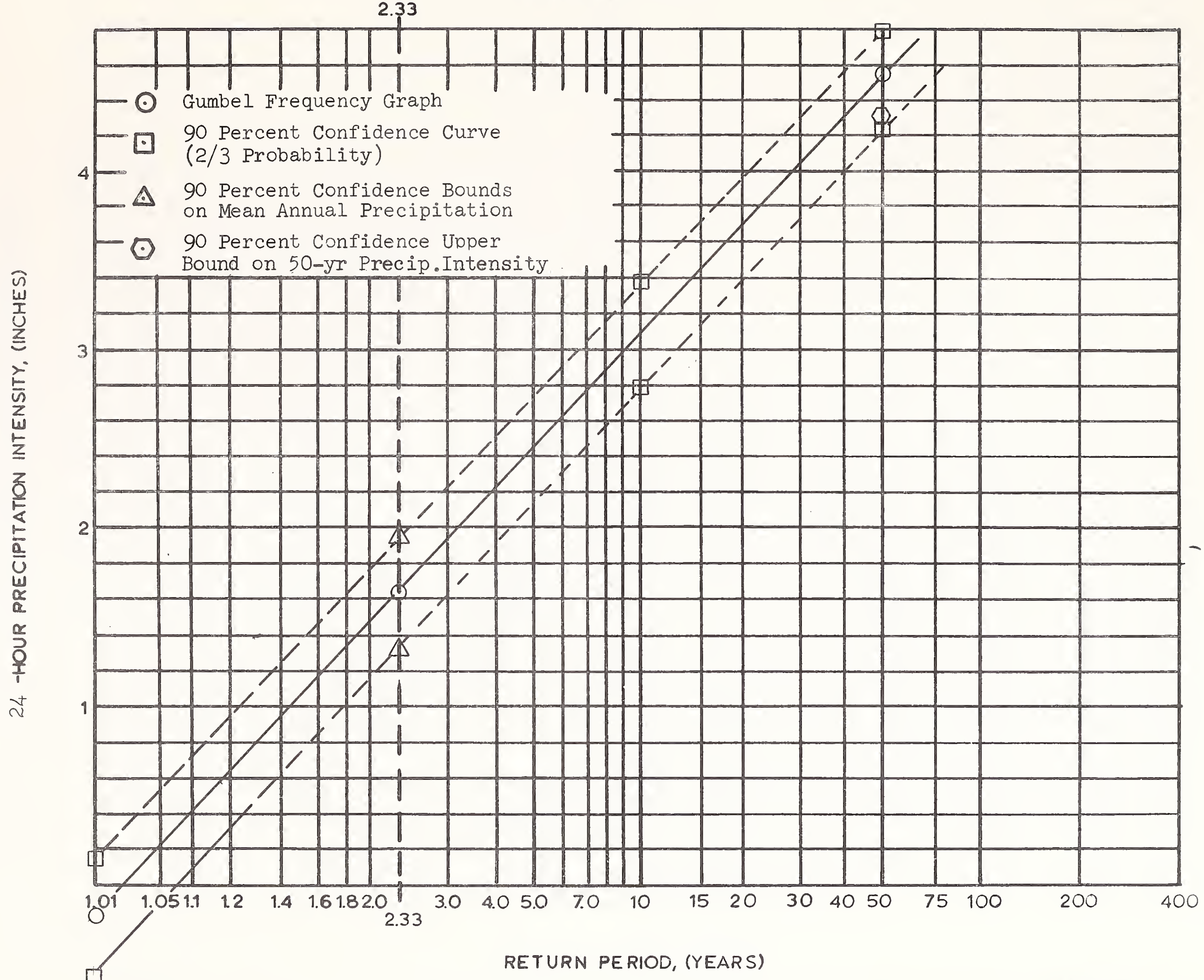


FIGURE 6 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Ekalaka

FORT BENTON

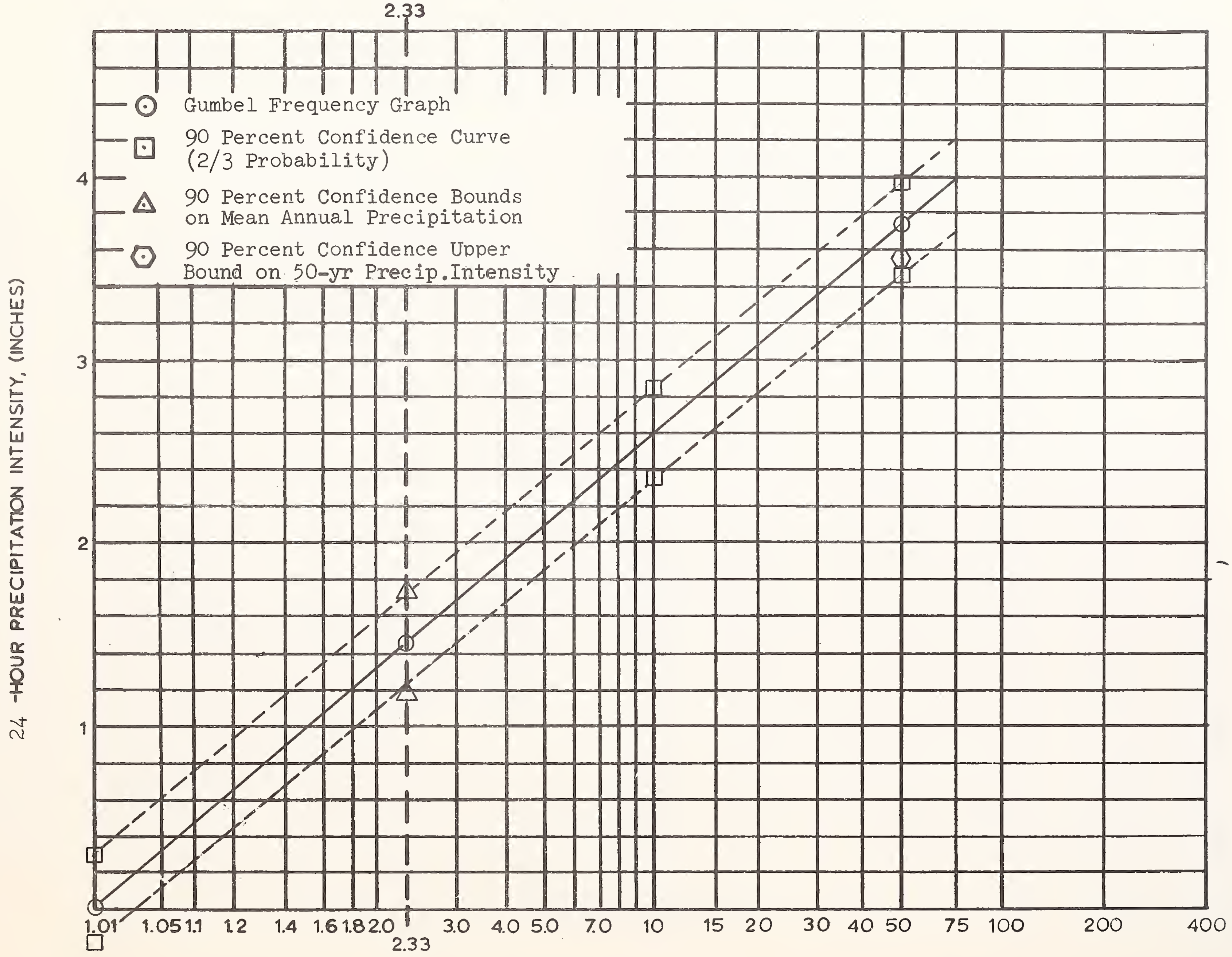


FIGURE 7 -- 90 Percent Confidence Bounds on Precipitation Intensity (24-hour) Ft. Benton

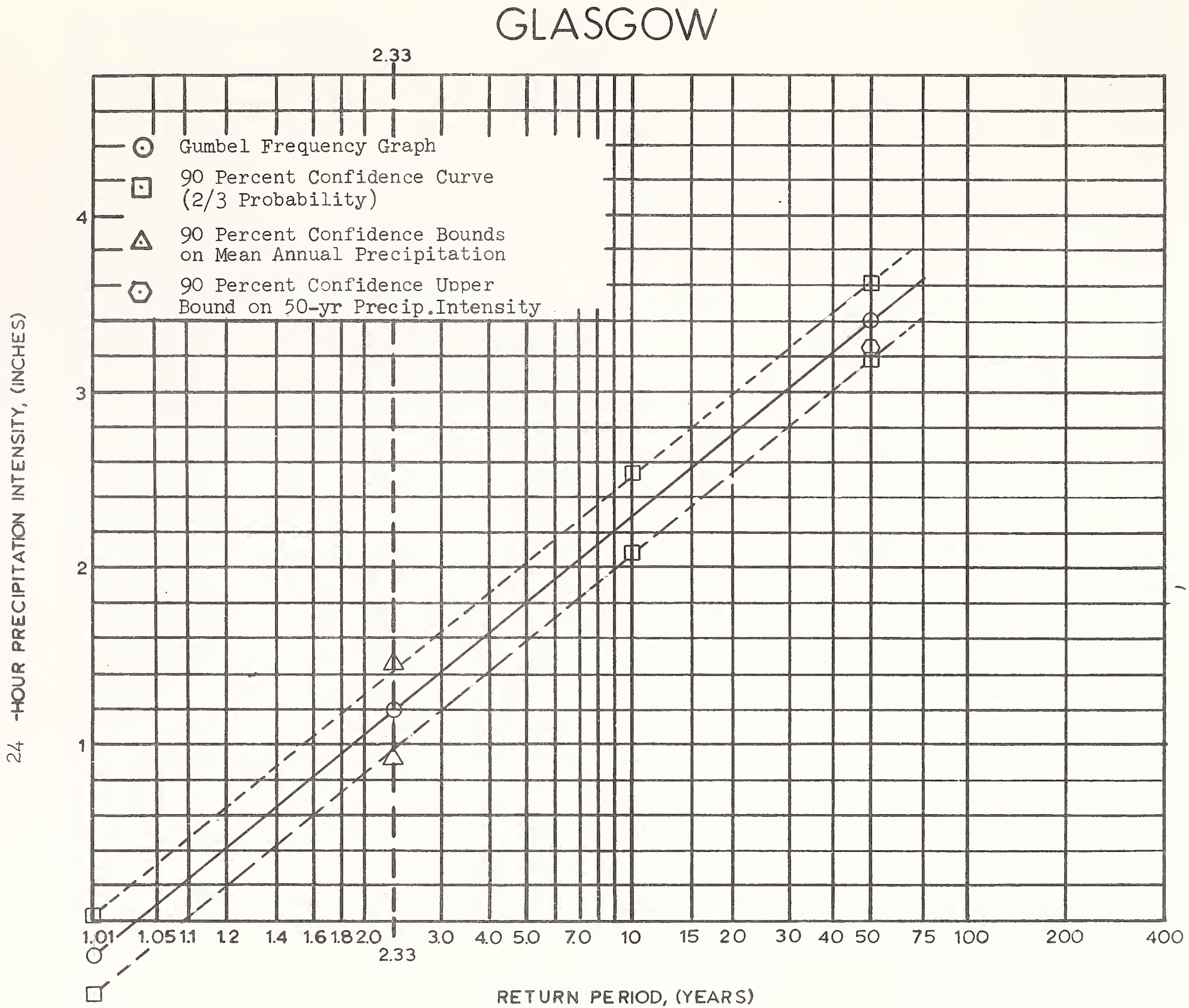


FIGURE 8 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Glasgow

GREAT FALLS

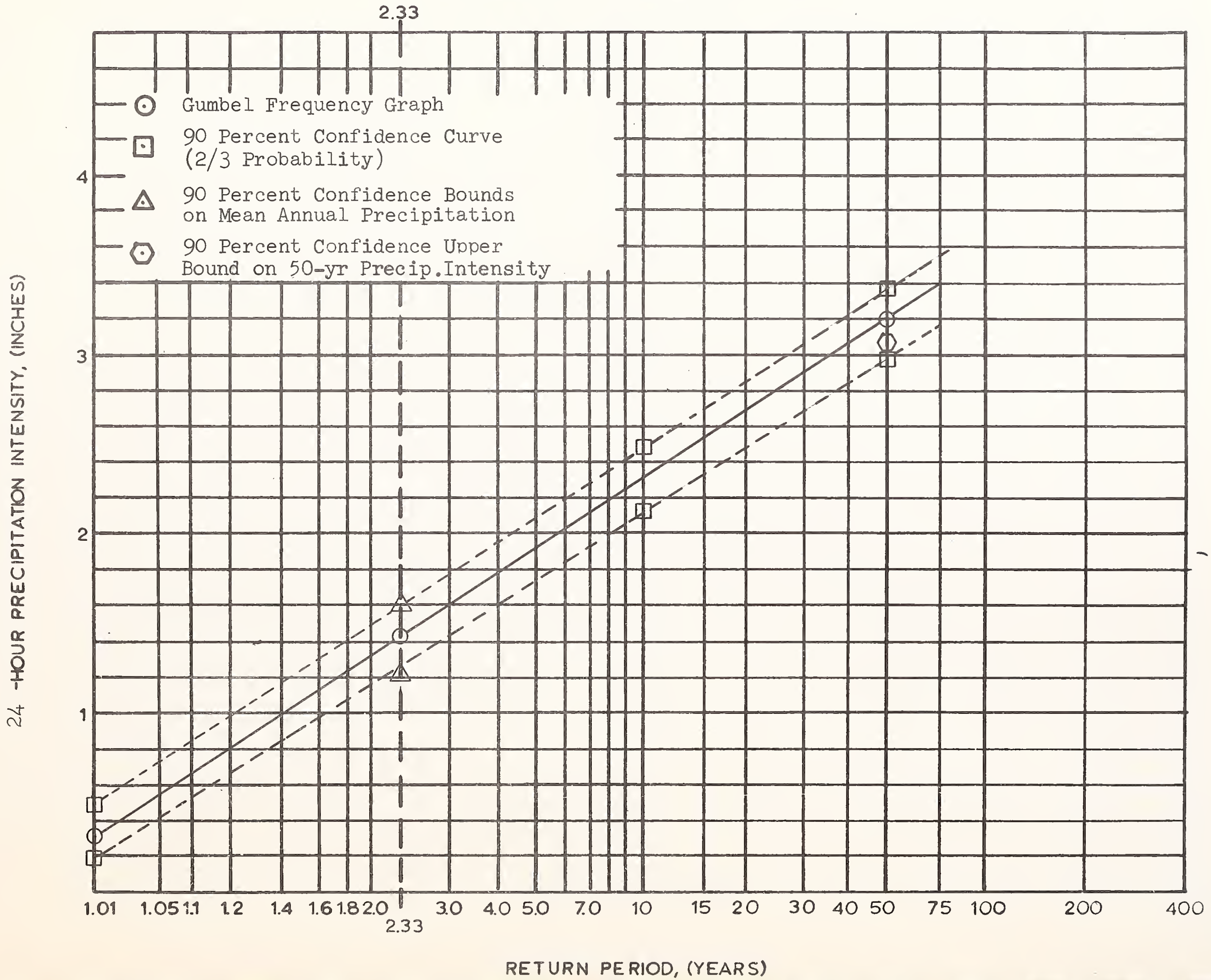


FIGURE 9 - [illegible] Pe[illegible]t C[illegible]ider[illegible] Bou[illegible]on [illegible]ipi[illegible]ion [illegible]ens[illegible] ([illegible]our[illegible] Gre[illegible]Fal.

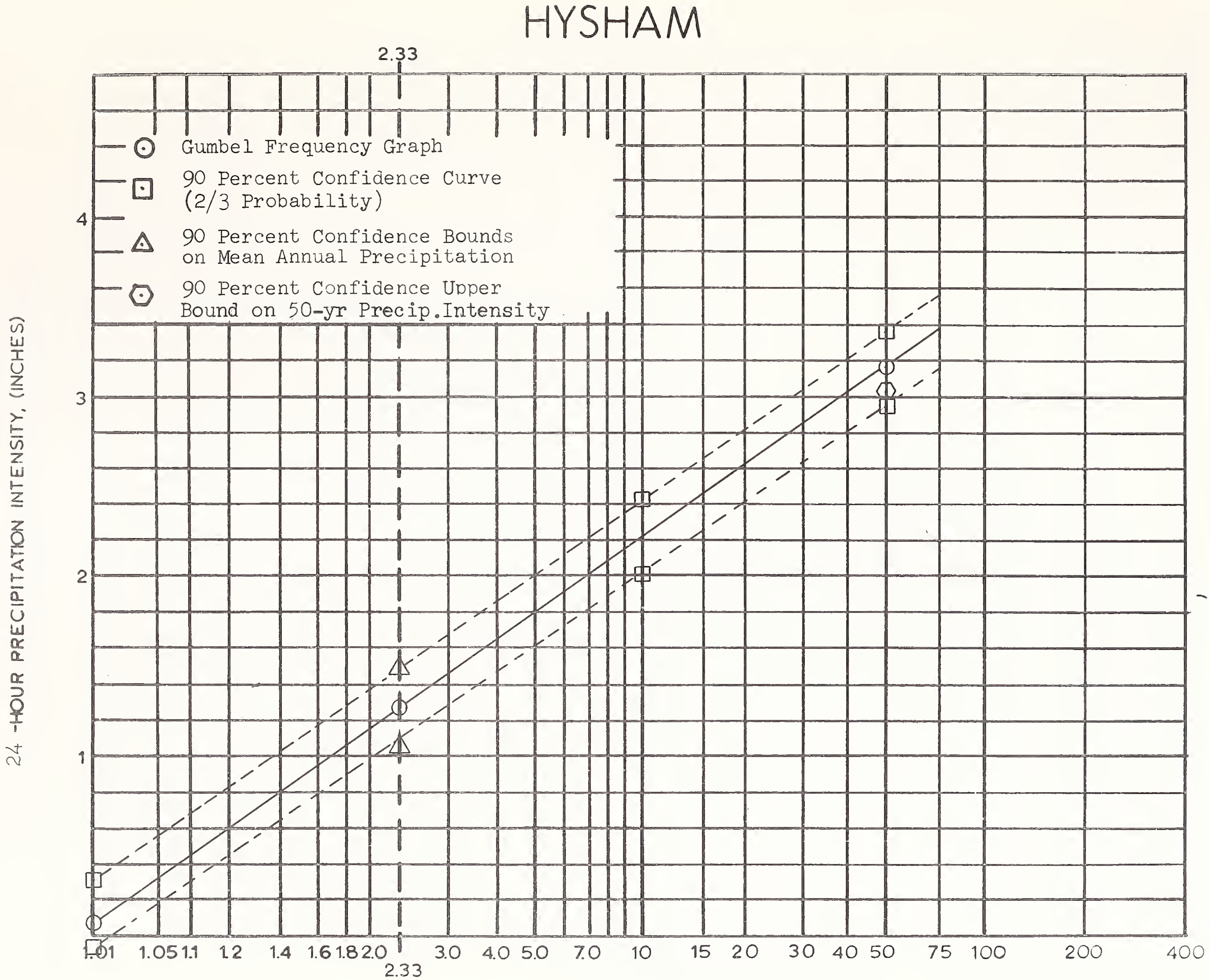


FIGURE 10 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Hysham

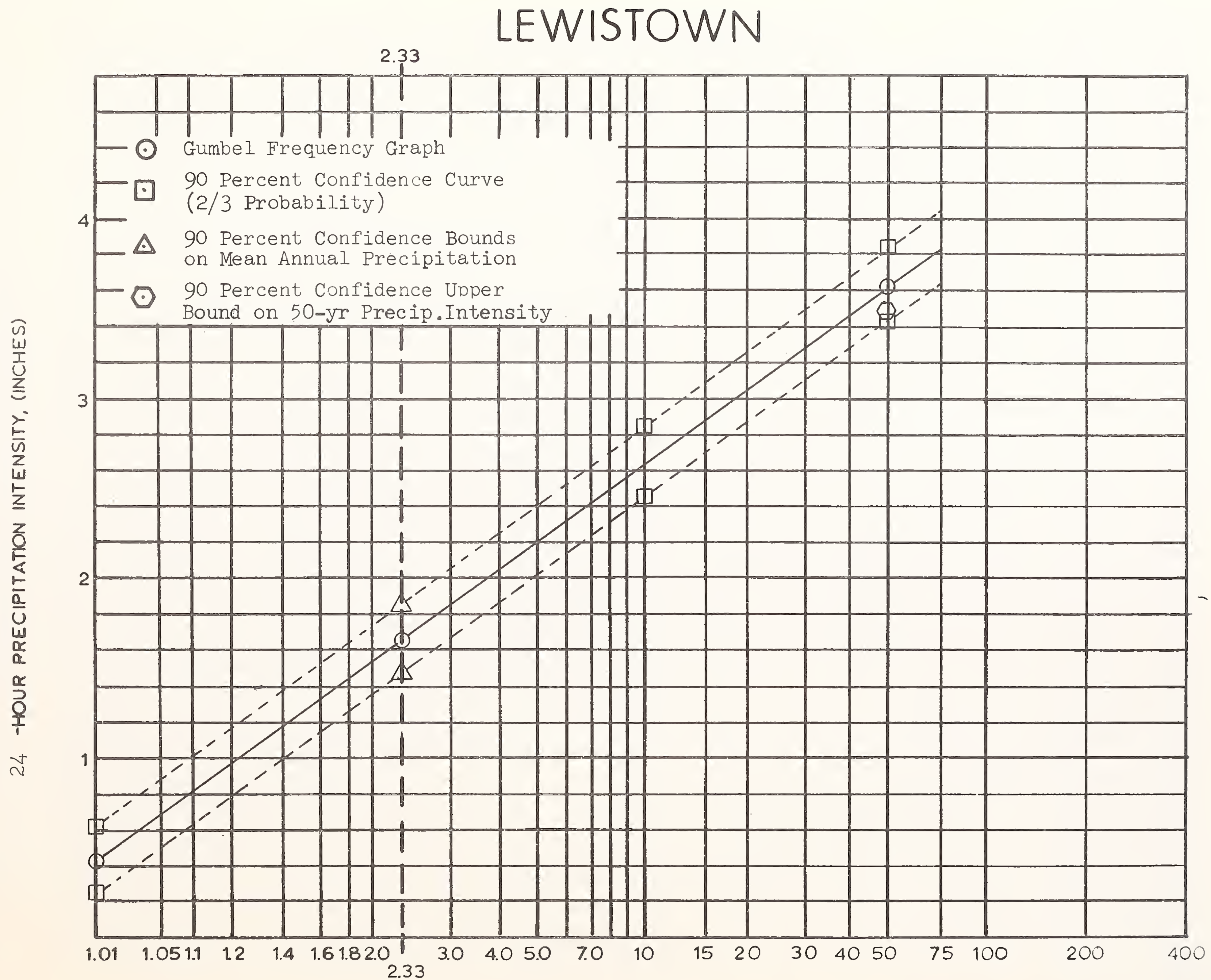


FIGURE 11 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Lewistown

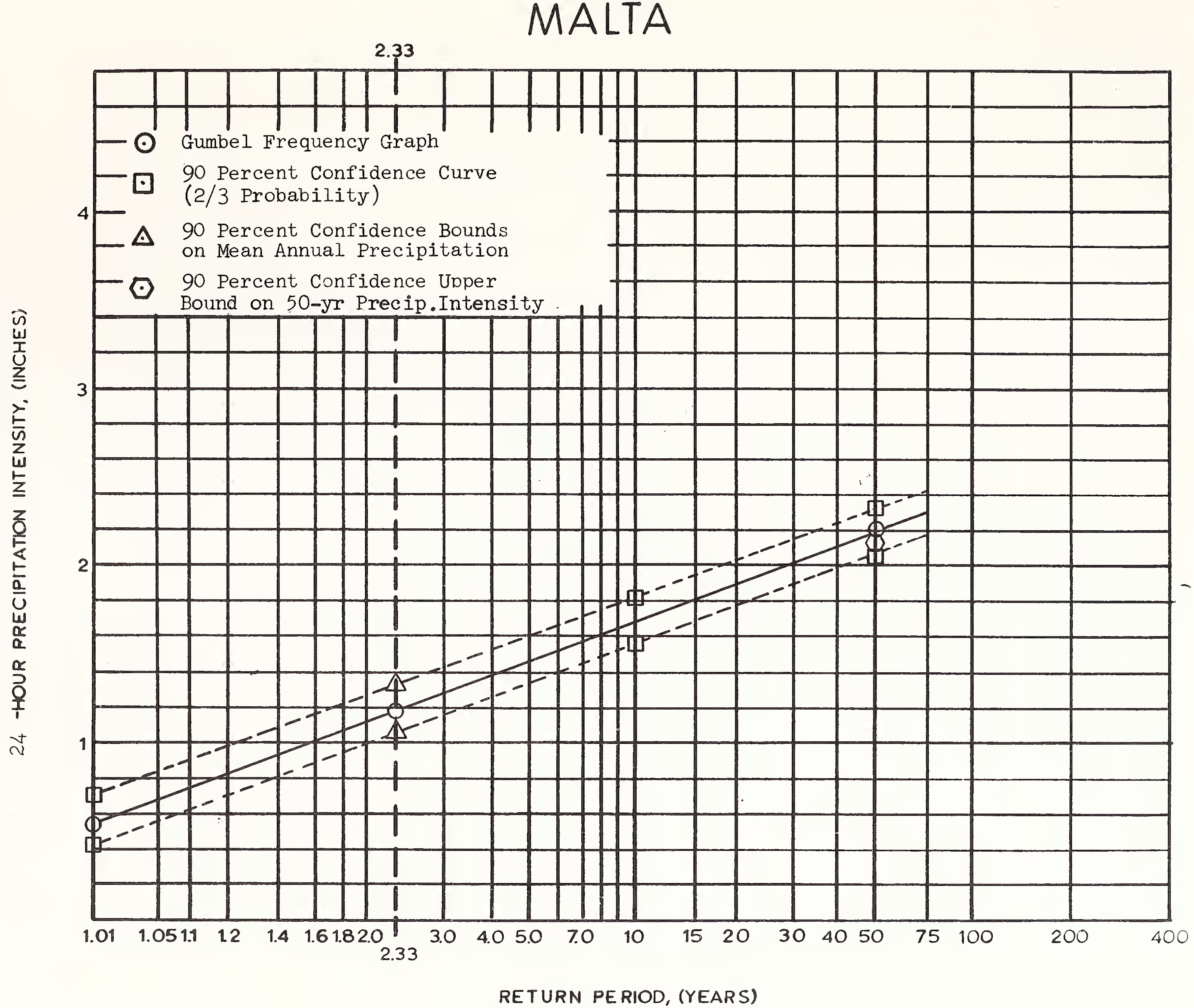


FIGURE 12 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Malta

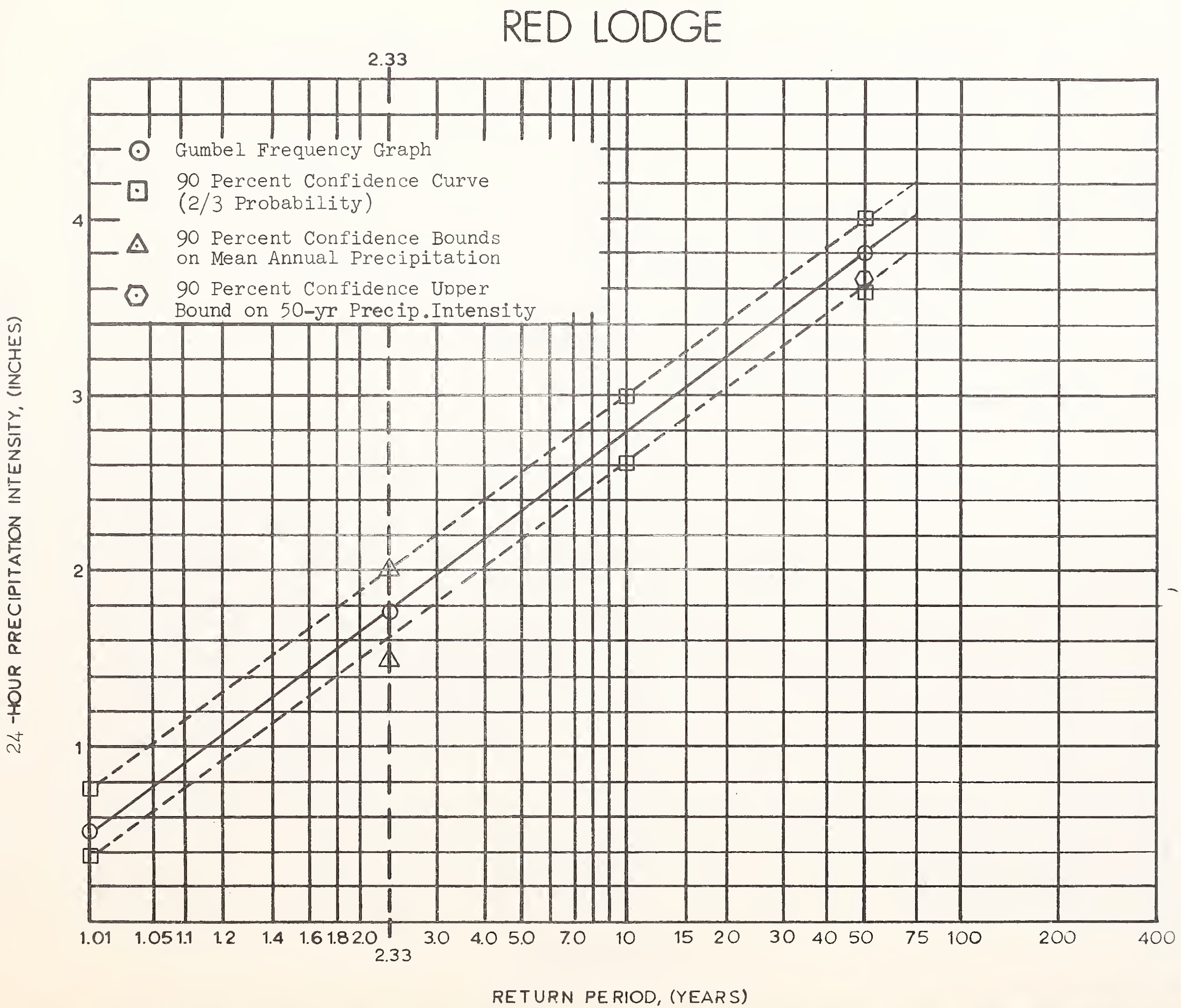


FIGURE 13 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Red Lodge

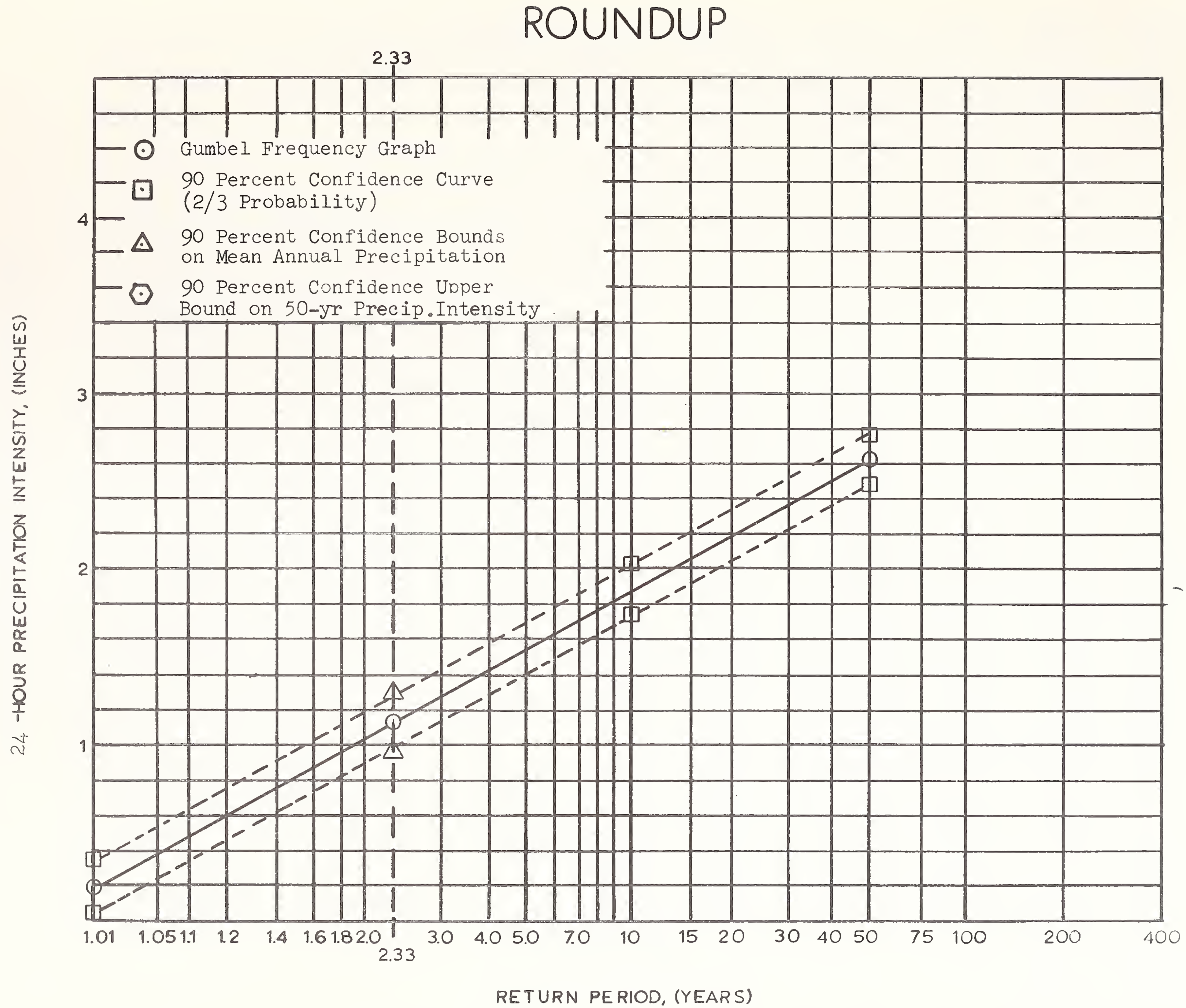


FIGURE 14 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Roundup

SIDNEY

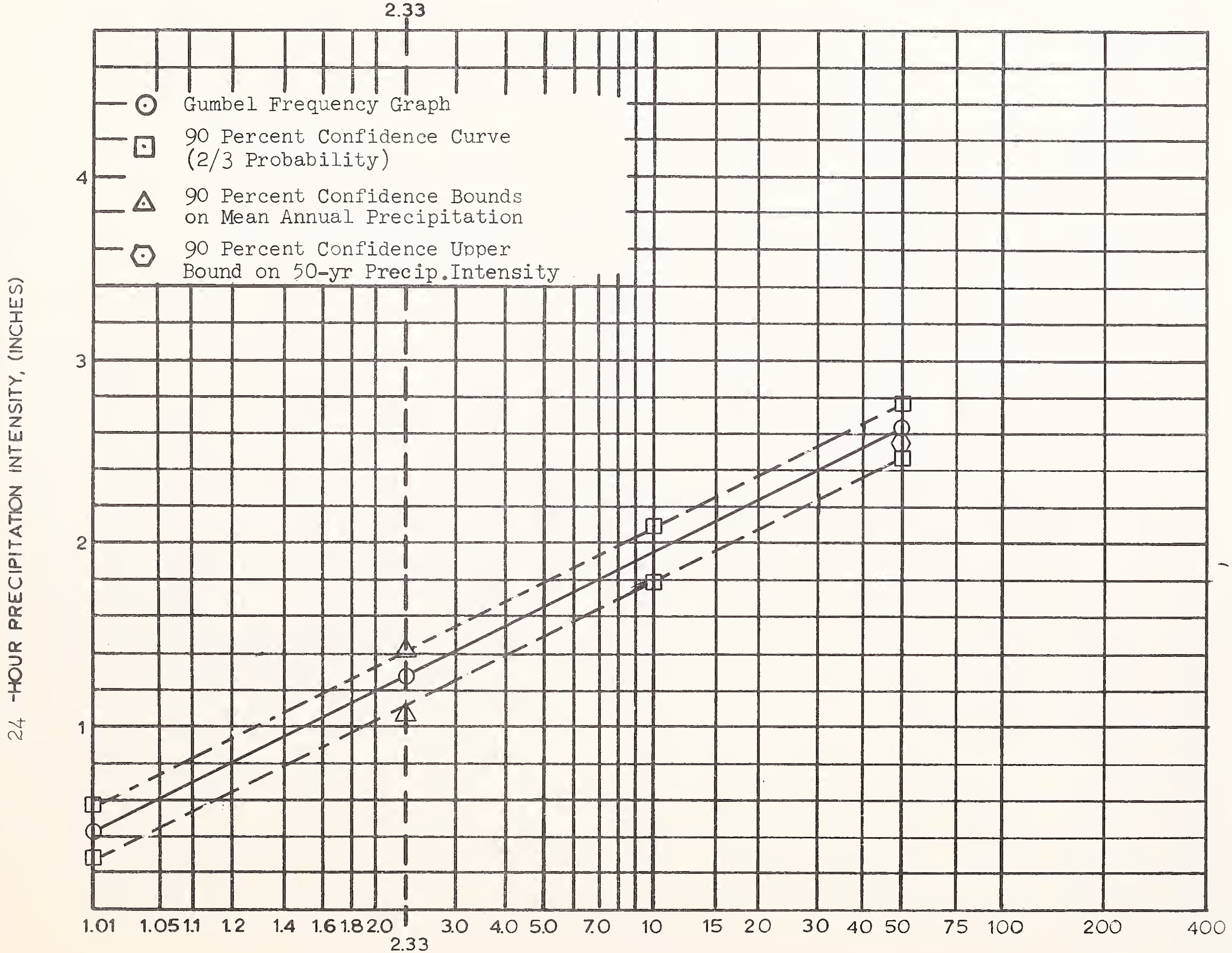


FIGURE 15 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Sidney

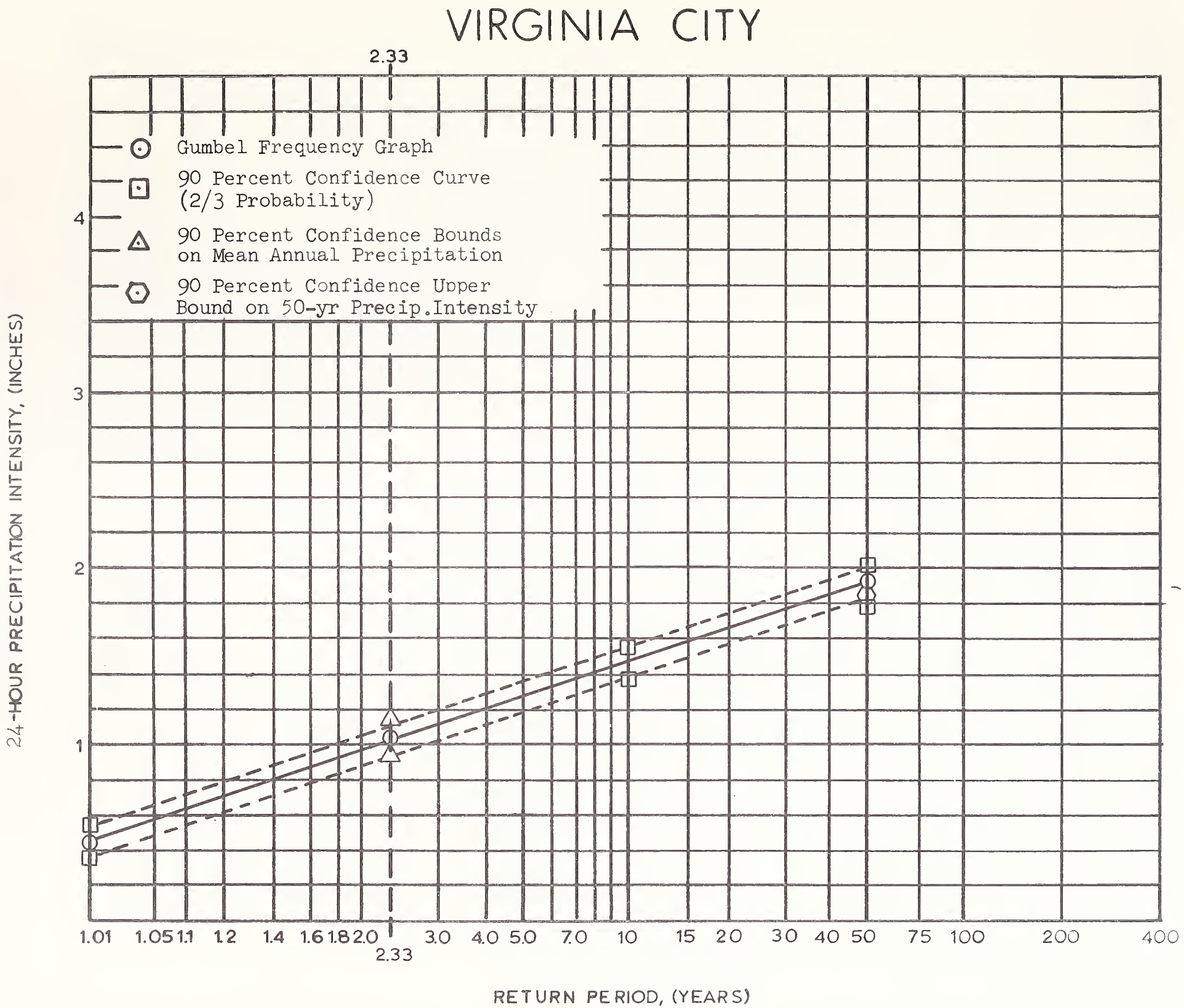


FIGURE 16 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Virginia City

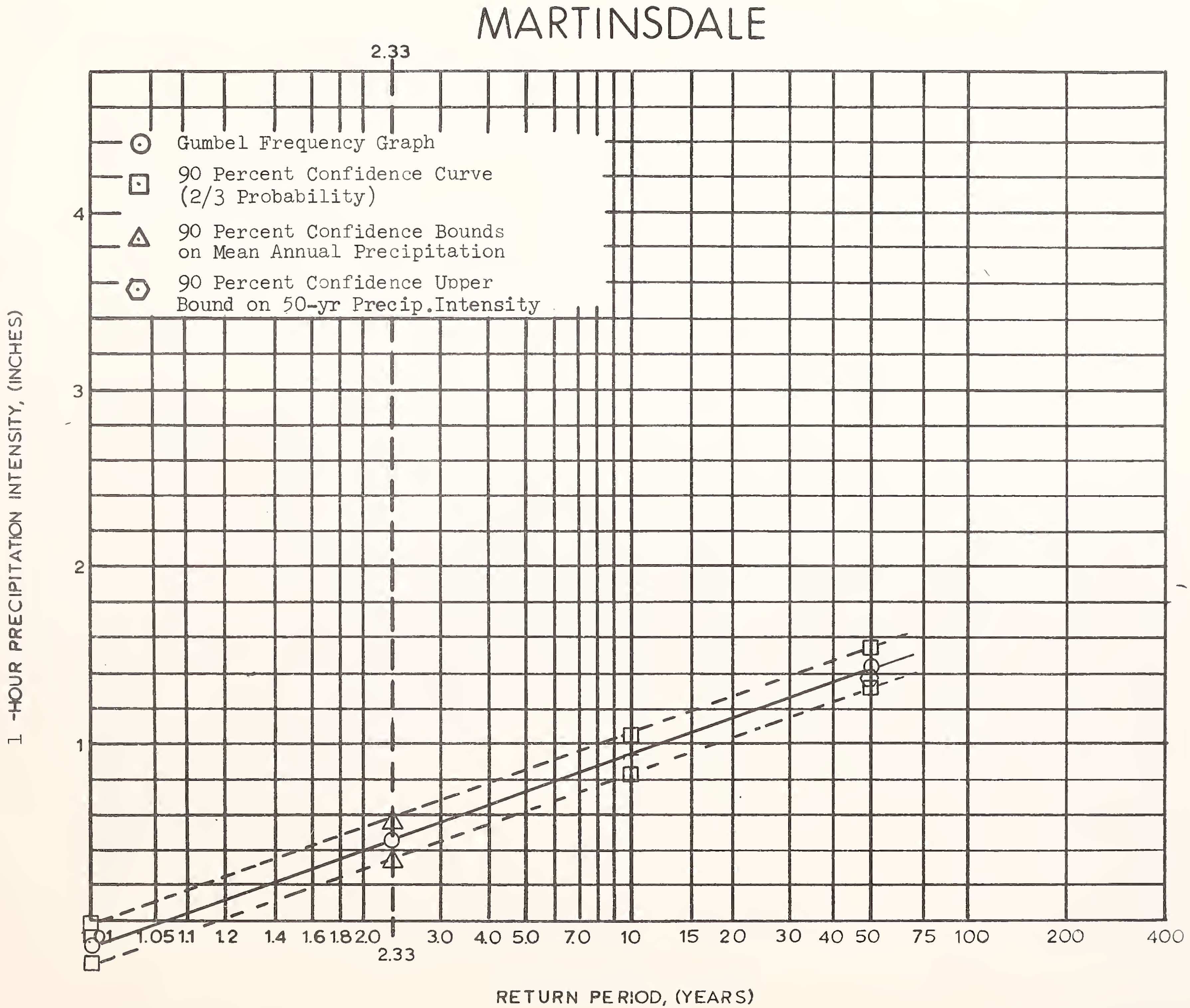


FIGURE 17 -- 90 Percent Confidence Bounds on Precipitation Intensity: (1 -hour) Martinsdale

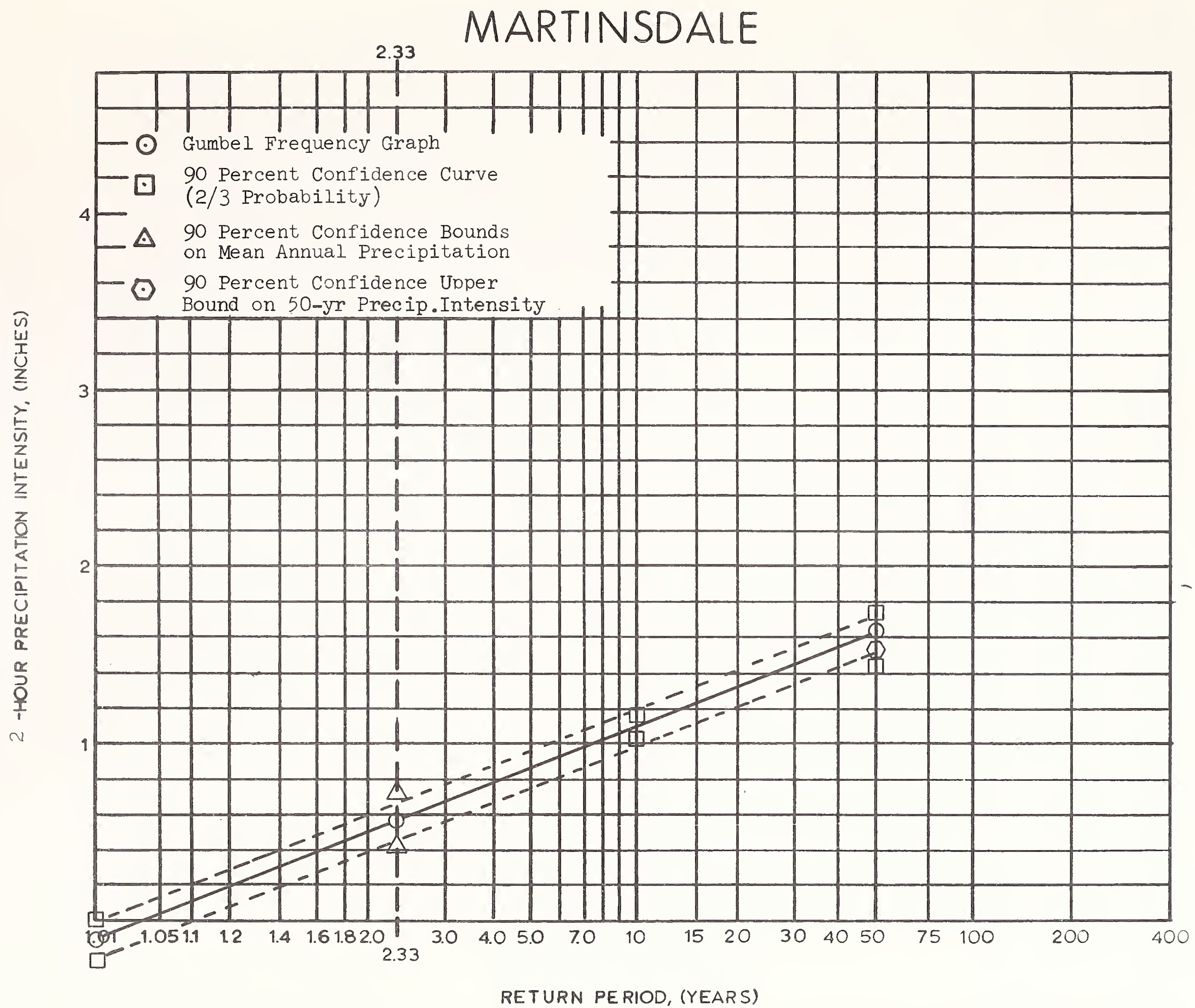


FIGURE 18 -- 90 Percent Confidence Bounds on Precipitation Intensity: (2-hour) Martinsdale

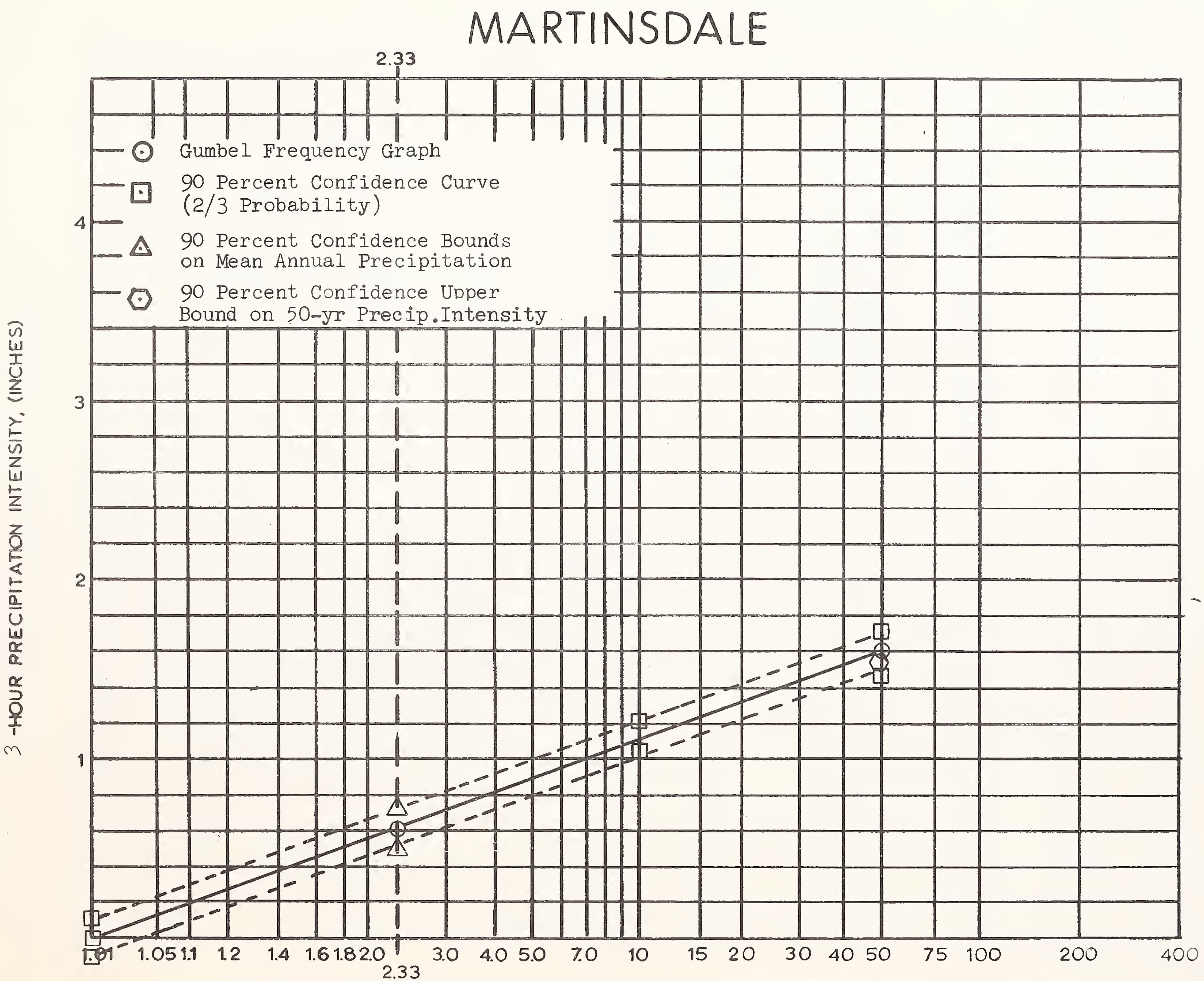


FIGURE 19 -- 90 Percent Confidence Bounds on Precipitation Intensity: (3-hour) Martinsdale

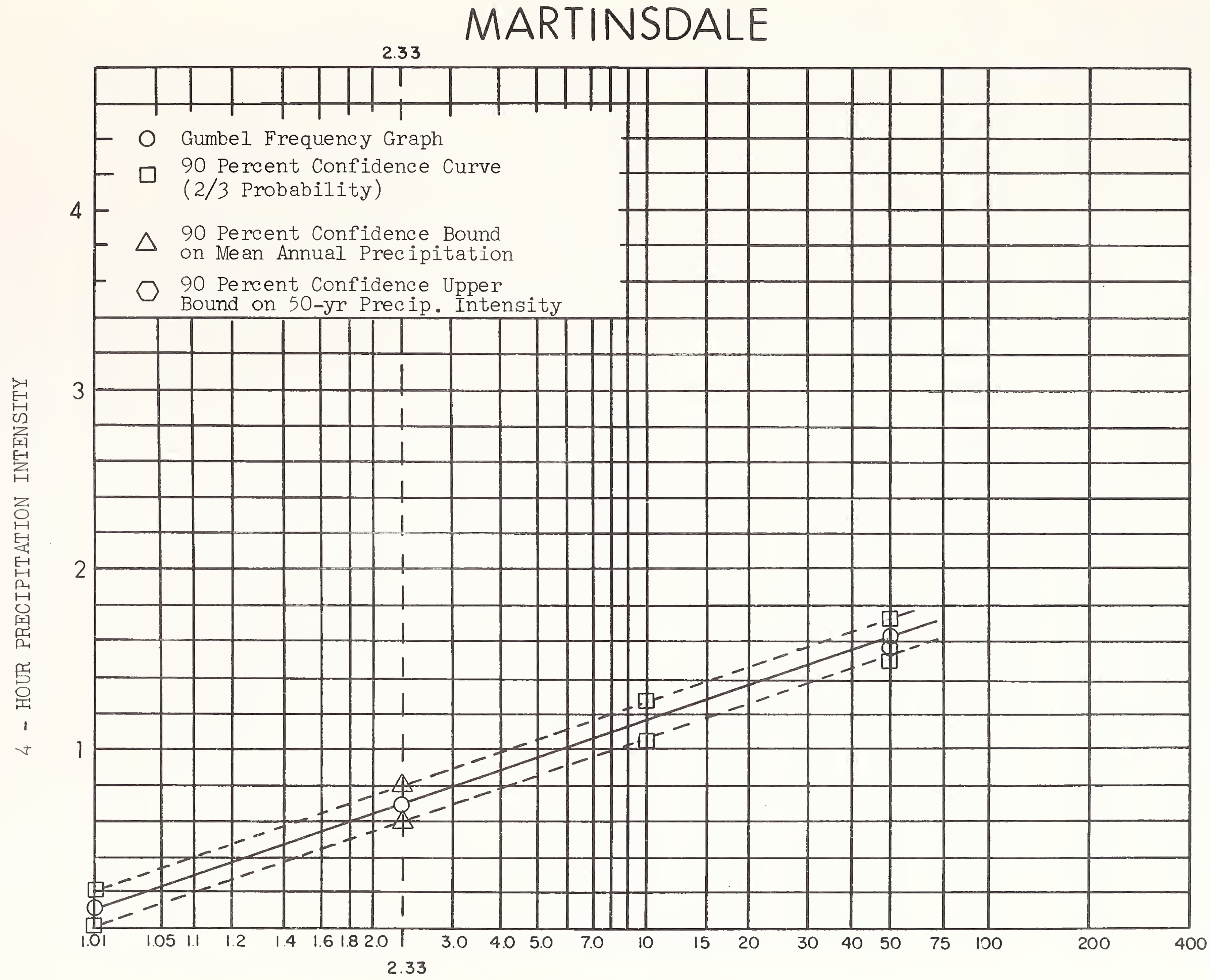


FIGURE 20 - 90 Percent Confidence Bounds on Precipitation Intensities: (4-hour) Martinsdale

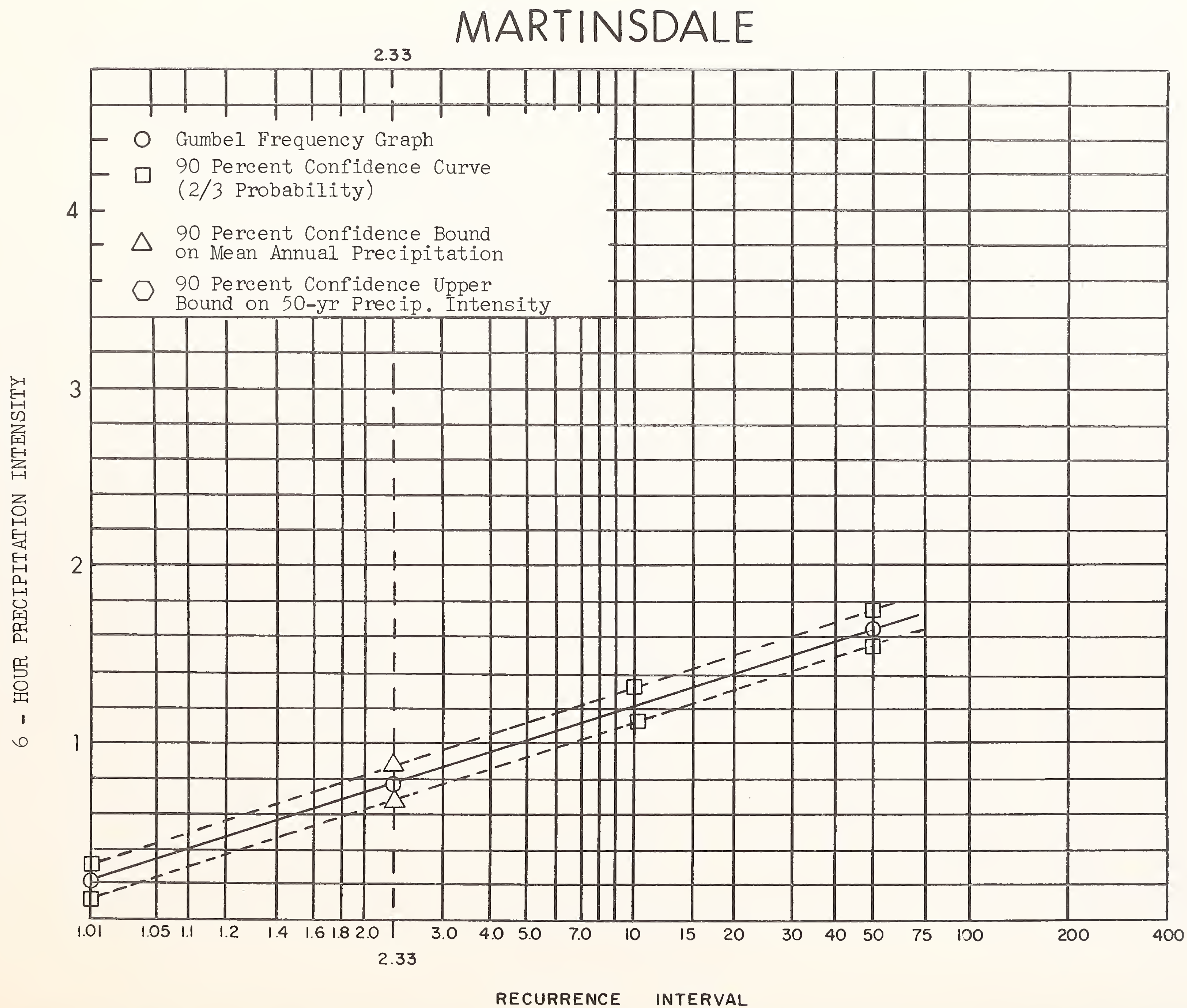


FIGURE 21 - 90 Percent Confidence Bounds on Precipitation Intensities: (6-hour) Martinsdale

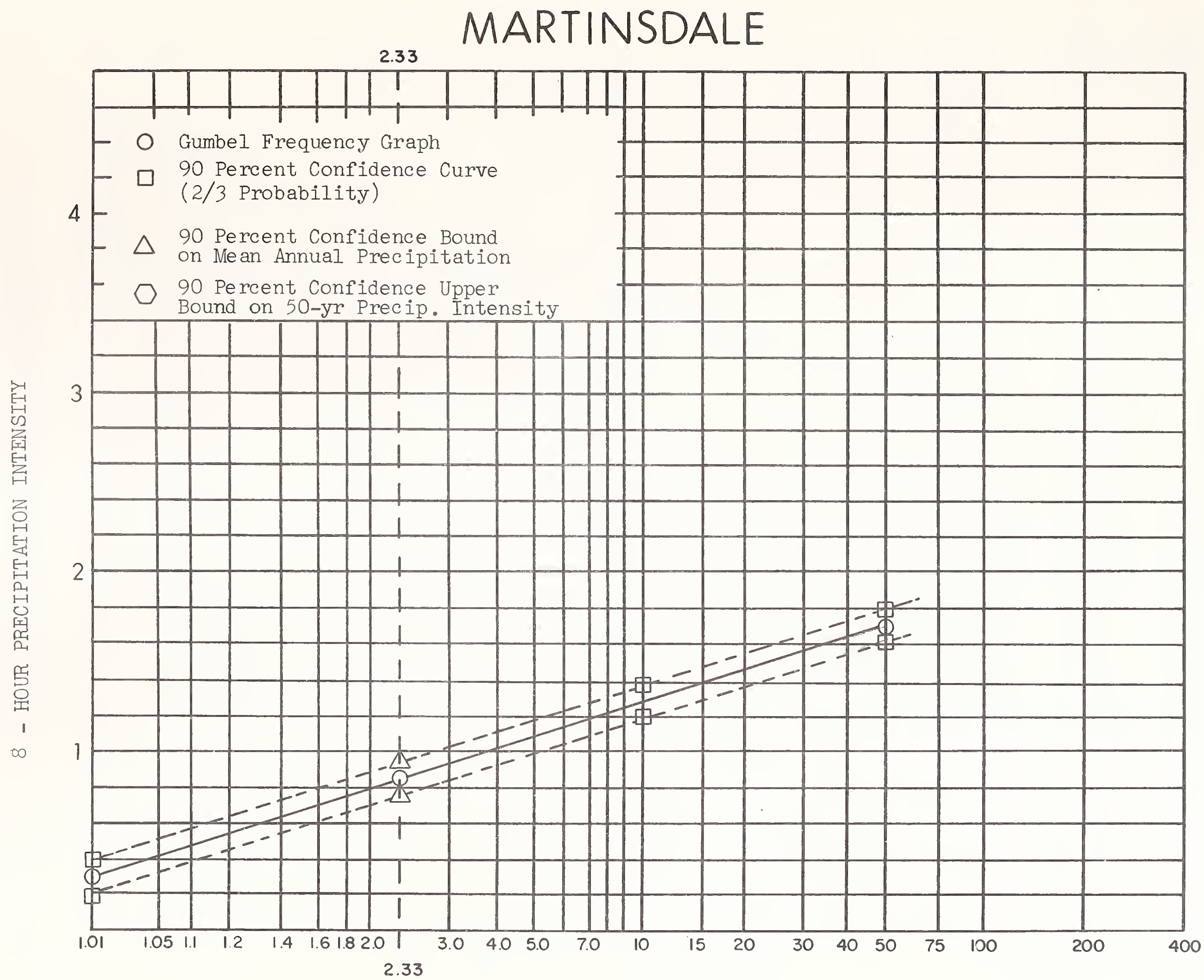


FIGURE 22 - 90 Percent Confidence Bounds on Precipitation Intensities: (8 -hour) Martinsdale

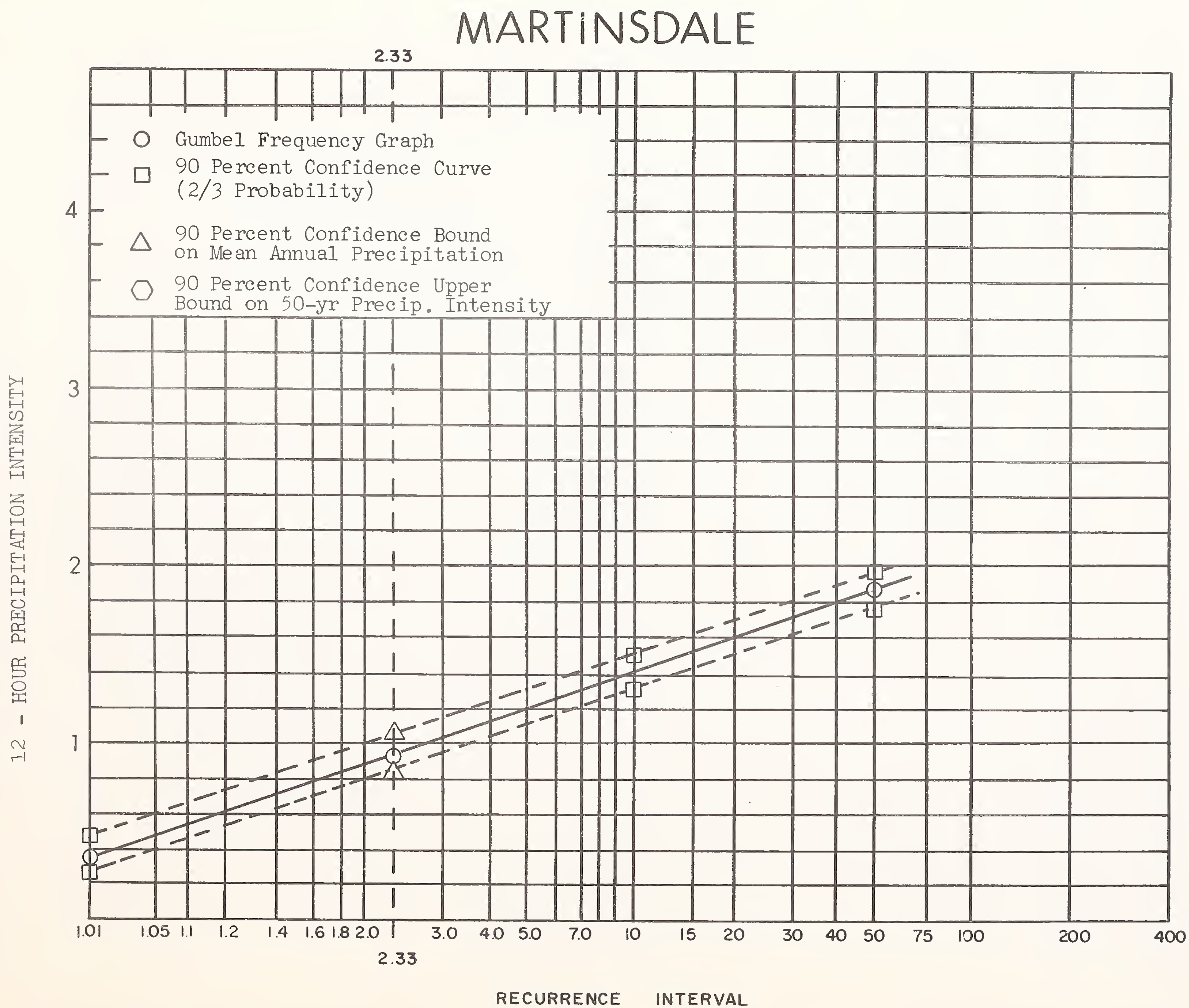


FIGURE 23 - 90 Percent Confidence Bounds on Precipitation Intensities: (12-hour) Martinsdale

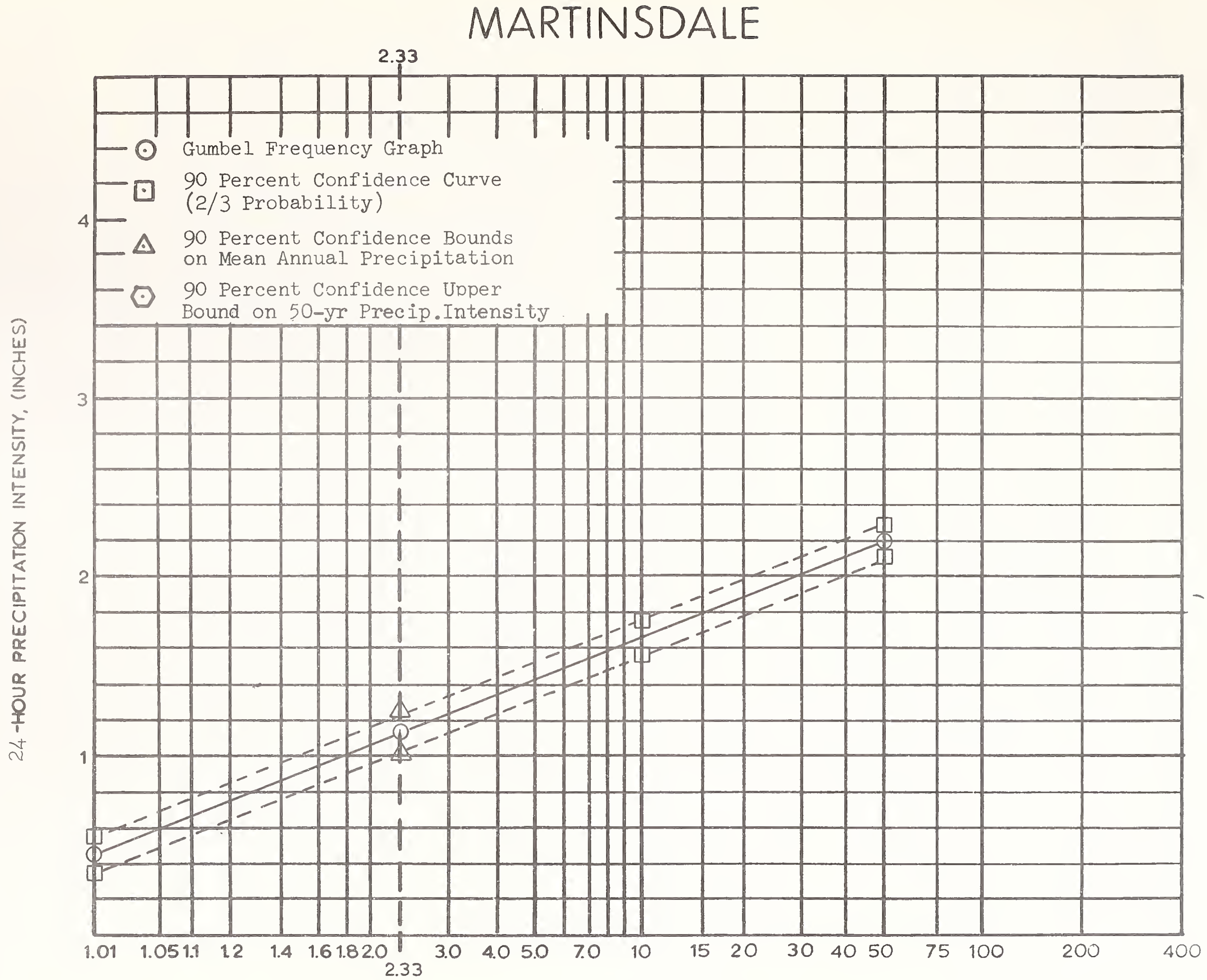


FIGURE 24 -- 90 Percent Confidence Bounds on Precipitation Intensity: (24-hour) Martinsdale

the population of precipitation intensities is normally distributed and determined by the Chi-square test:

$$\chi^2 = \frac{(n - 1)\ S^2}{\sigma^2} \tag{5}$$

where χ^2 = chi-square

(90% probability used)

n = number of years record

S = sample standard deviation

σ = population standard deviation

In each case the assumption of normal distribution produces a 50-year precipitation intensity which is within the 2/3 confidence limits using Gumbel's technique, but lower than Gumbel's 50-year value.

Study of Figures 4 to 24 leads to the conclusion that the Gumbel technique may be successfully applied to precipitation intensities in eastern Montana.

2. Woo questioned whether the rainfall frequency-peak flow frequency method does indeed predict comparable 50-year discharges as well as do the extreme value (Gumbel) or log-normal methods. Figures 2 and 3 show comparisons of results obtained using these three methods on 46 streams. Data for these figures are given in Table I. Table I also shows pertinent values for the computation of the F statistic which is used to determine whether or not there is any significant difference in the three methods. The three methods were tested together, and also by pairs. Table I shows the values of F which would be "significant" at the 99% confidence level. Since the computed values of F are all much lower than the "significant" F, the conclusion is that at the 99% confidence level no significant difference can be detected in the results obtained by using the three methods.

The F statistic is obtained as the ratio of treatment mean square to error mean square.

Treatment mean square = treatment sum of squares/degrees of freedom.

Error mean square = error sum of squares/degree of freedom

$$\text{Treatment SS} = \frac{\sum((\sum x_i)^2}{r} - \frac{(\sum(\sum x_i))^2}{rt} \qquad (6)$$

$$\text{Error SS} = \sum(\sum(x_i^2)) - \frac{\sum((\sum x_i)^2)}{r} \qquad (7)$$

Treatment degrees of freedom = t - 1

Error degrees of freedom = t(r-1)

x_i = a value of 50-year peak discharge at station i computed by one of the 3 methods.

r = number of stations (46 in this case)

t = number of methods (either 2 or 3 in this case).

3. Woo noted that the method cannot be verified because there are no exact correct values to be used for comparison. There can be no argument with Woo's statement, but it must also be applied to the Gumbel technique, the log-normal method, the Log-Pearson Type III method, or indeed to any method which purports to predict the magnitude of a flood peak having a specified return period. The contention that the method is not usable because of the absence of actual long records is not believed to be valid.

4. Woo pointed out that the values of R, D and F used for estimating peak-discharges were derived from drainage areas of 30 to 700 square miles, and that the method should not be used to predict peak flows from drainage areas outside this range of areas. This is a valid point, and should be adhered to.

TABLE I. Comparisons of Estimates of Q_T^{50} by Three Methods.

U.S.G.S. Station No.	Watershed	Area, sq. mi.	Years Record	Mean Annual Flow (cfs)	Coefficient of Variation (%)	Estimate of 50-year Peak Q_T^{50} (cfs) Gumbel[a]	Chow[b]	Robinson[c]
135	Sheep Creek	280	15	354	53.8	994	878	800
155	Grasshopper Cr.	348	30	446	72.7	1420	1387	1010
465	E. Gallatin R.	49	10	320	43.7	813	697	802
470	Bear Canyon Cr.	17	10	164	66.8	552	481	412
760	Newland Creek	6.74	15	17.8	84.8	68.5	62.2	42.9
893	Sun River Trib.	21.1	11	124	119.3	435[d]	382	313
1003	Lone Man Coulee	14.1	7	339	186.4	682[d]	501	917
1022	Marias R. Trib.	1.6	11	40.9	217.4	354	268	110
1023	Marias R. Trib. #2	0.2	11	10.3	125.6	55.8	42.7	27.8
1206	Antelope Cr.Trib	0.5	11	3.0	134.2	17.5	13.2	7.9
1207	Antelope Cr.Trib	1.9	11	77.3	94.9	336	296	203
1208	Bacon Creek	21.2	11	225	145.9	1383	1094	590
1209	Antelope Creek	88.7	14	2090	308.1	23730	20377	5480
1289	Box Elder Cr.	16.2	12	155	71.7	546	477	488
1295	McDonald Creek	421	28	369	86.9	1372	1321	1874
1297	Gorman Coulee	2.32	11	95.2	124.0	512	392	315
1298	Gorman Coulee Trib.	0.8	12	52.4	107.0	250	220	174
1306	Cat Creek	36.5	9	190	123.5	1053	781	629
1308	Second Cr. Trib	1.9	10	71.5	182.9	533	413	313
1395	Big Sandy Cr.	1805	21	827	159.2	4939	4093	2420
1552	Alkali Creek	162	9	346	92.8	1525	1300	1150
1553	Disjardin Coulee	3.4	11	97.0	113.9	487	427	319
1554	S.Fk.Taylor Cr.	5.1	11	29.1	114.6	147	129	96
1765	Wolf Creek	251	22	1032	232.9	8697	7632	5330
1770.5	E.Fk. Duck Cr.	12.4	12	219	85.1	878	769	1050
1771	Duck Creek	54.0	10	441	88.6	1820	1599	2530
1771.5	Redwater Creek	216	10	843	55.2	2486	2138	4020
1772	Tusler Creek	90.2	10	186	67.6	630	549	883
1773	Redwater Ck.Trib	0.3	11	41.8	166.6	287	225	199
1773.5	S.Fk.Dry Ash Cr.	5.7	12	40.4	733	145	126	192
1774	McCune Creek	29.9	11	226	125.7	1230	986	1070
1830	Big Muddy Creek	850	19	1731	1308	9062	7404	9500
1831	Box Elder Creek	9.4	11	119	88.4	492	432	650
1832	Box Elder Creek	19.9	10	1163	166.6	8000	6256	4400
1833	Spring Creek	7.0	12	49.1	132.9	279	212	270
1834	Spring Creek	16.9	12	262	105.7	1240	1090	1430
2162	Wets Creek	8.1	12	118	132.0	667	533	348
2163	W. Buckeye Creek	1.5	12	93.6	83.3	369	324	276
2165	Pryor Creek	435	42	750	82.0	2597	2570	2230
2960	Rosebud Creek	1260	19	301	64.8	932	859	1150

[a]Extreme Value (Gumbel) Estimate.

[b]Log-Normal (log probability) Estimate. (Chow)

[c]Peak Rainfall Frequency-Peak Flow Estimate.

[d]Adjusted for the Event of June 1964.

TABLE I. Comparisons of Estimates of Q_T^{50} by Three Methods. (Cont'd)

U.S.G.S. Station No.	Watershed	Area, sq. mi.	Years Record	Mean Annual Flow (cfs)	Coefficient of Variation (%)	Estimate of 50-year Peak Q_T^{50} (cfs) Gumbel[a]	Chow[b]	Robinson[c]
3082	Basin Creek Trib	0.1	12	52.2	209.8	439	351	205
3083	Basin Creek	10.9	12	412	92.6	1756	1545	1620
3247	Sand Creek	10.6	12	56.2	134.8	324	258	224
3329	North Creek	0.7	13	312	104.0	1403	1283	1310
3341	Wolf Creek	9.1	12	396	75.9	1456	1274	1610
3364.5	Spring Creek	3.9	11	111	102.8	515	454	590

[a]Extreme Value (Gumbel) Estimate.

[b]Log-Normal (log probability) Estimate.

[c]Peak Rainfall Frequency-Peak Flow Estimate.

	Gumbel	Chow	Robinson
ΣX	87908.8	74901.1	59580.8
$\Sigma(X^2)$	852593000	618457000	225599000
$(\Sigma X)^2/N$	167999000	121960000	77170800

		D.F.	SUM SQUARES	MEAN SQUARE	F	$F_{(.01)}$
Gumbel-Chow-Robinson	Among Methods	2	8,742,000	4,371,000	.443834	4.61
	Within Methods	135	1,329,520,000	9,848,290		
		137	1,338,262,000			
Gumbel-Chow	Among Methods	1	1,839,130	1,839,130	.140143	6.97
	Within Methods	90	1,181,090,000	13,123,200		
		91	1,182,930,000			
Gumbel-Robinson	Among Methods	1	8,722,620	8,722,620	.942395	6.97
	Within Methods	90	833,022,000	9,255,800		
		91	841,745,000			
Chow-Robinson	Among Methods	1	2,551,250	2,551,250	.356029	6.97
	Within Methods	90	644,925,000	7,165,830		
		91	647,476,000			

CONCLUSIONS

The rainfall frequency-peak flow frequency method is an important contribution to small watershed hydrology. For a watershed with at least a short-term streamflow record available it can be applied rapidly by simple formulas. It does not require extensive field data. It is unique among methods reported in the literature in that it utilizes long-term precipitation data, which are available in quantity, to determine variance from mean annual flood peak. It has been shown to give results that are comparable to those obtained from other methods.

Further work is needed to refine the procedure and extend it to other geographical areas and other return periods.

SUMMARY

The development of a rainfall frequency-peak flow frequency method for predicting peak discharges of given recurrence interval is discussed herein. The statistical comparisons and tests which have been made are believed to answer the principal objections raised by the Federal Highway Administration reviewer of Interim Report #7.

CHAPTER III

HYDROLOGIC STUDY OF FOUR SELECTED WATERSHEDS

Phase II of the Proposal for this Project envisioned the comprehensive hydrologic study of four widely separated watersheds for the purpose of extending the usefulness of the U.S. Geological Survey "Small-Area Peak-Flow-Highway Program." This chapter defines the scope of the studies that have been made, describes the procedures used, and discusses data collection and reduction techniques and problems.

SELECTION OF WATERSHEDS

The first criterion for selecting the watersheds that were to be studied was that they must be watersheds that had already been included in the U.S.G.S. investigation, and for which at least a few years of crest-stage gage measurements were available. In conference with Hydraulics Division personnel of the State Highway Department, and representatives of the U.S.G.S. and U.S. Weather Bureau, some guidelines for watershed selection were set forth. The area west of the continental divide was eliminated because relatively few flood problems on small watersheds west of the divide could be cited. It was agreed that all the watersheds should be in plains environments, and several general areas of the state were suggested.

Thirteen watersheds were visited and inspected before the four study watersheds were selected. Brief descriptions of the watersheds visited were included in Interim Report #1 (Williams, 1965). Maps and aerial photographs of the watersheds selected are presented in Appendix B .

Bacon Creek, in Wheatland County drains 21.2 square miles, and is a tributary of Antelope Creek which in turn is tributary to the Musselshell River. Bacon Creek watershed is an almost exclusively range area (mostly sheep grazing) due north of Harlowton. Drainage is predominantly northwest to southeast. There is essentially no timber on the watershed. It has had a history of occasional extreme flood events, the largest event of record having been in June, 1950.

Duck Creek, in Prairie and McCone Counties drains 54.0 square miles, and is a tributary of Redwater River. The watershed has two main streams, East Duck and West Duck, which merge a short distance above the mouth of the watershed. Drainage is northerly. The watershed extends south to Sheep Mountain, which is the divide between the Yellowstone and Missouri drainages. The higher elevations are rough and broken, similar in character to many Badlands areas. This portion of the watershed is used almost exclusively for range and livestock grazing. Near the mouth of the watershed slopes are gentle to rolling and a considerable portion of the area is in dryland wheat.

Hump Creek, in Sweetgrass County, drains 7.6 square miles, and is a direct tributary of the Yellowstone. Drainage is to the north. Mouth of the watershed is two miles west of Reed Point. This is the smallest of the watersheds selected, and is the only one with significant growths of timber, (mostly scrub pine). The basin is steep, and is characterized by numerous side-canyons which are tributary to the main stream. The basin is mostly covered with native grass and is used for livestock grazing.

Lone Man Coulee, in Pondera County, drains 14.6 square miles, and is located five miles south of Valier, and about two miles south of Lake

Frances. The watershed is tributary to the Dry Fork of the Marias River. Drainage is from west to east. Slopes are gentle and most of the basin is in cultivated strip-wheat farming. The largest flood of record at Lone Man Coulee was a flow of 1820 cfs in June 1948, but this was almost matched by a flow of 1740 cfs in June 1964. The 1964 flood was the subject of a special interim report. (Williams, 1964).

PHYSICAL CHARACTERISTICS

A compilation of physical characteristics of the project watersheds is in Appendix C . Included are data related to area, shape, elevation, slope, stream length, stream density, orientation, pondage, and land use.

Topographic maps, aerial photographs and field studies were utilized in the determination of the parameters. The soil investigations in particular were quite extensive and will be discussed separately.

Soils Investigation

Soil analyses on the four project watersheds included mechanical analysis and Atterberg Limit determinations; medium intensity soil surveys by soil scientists of the Soil Conservation Service, USDA; and water intake studies.

Mechanical Analysis and Atterberg Limits: Soil samples were obtained from 3-inch, 9-inch and 18-inch depths at each of the eight weather station instrument enclosures at the time of installation of the instruments in 1964. The depths were selected to coincide with the depths specified for soil moisture and soil temperature element installation.

Combined sieve and hydrometer analysis were made on each sample, sieve sizes included 1-inch, #4, #20 and #40, with the hydrometer being used on the -40 fraction. Particle diameters as small as 0.001 millimeter were determined.

Liquid limit and plastic limit were determined for each sample, and plasticity index was calculated.

Summary soil data are shown in Appendix D .

Soil Surveys: The Montana State Office of the Soil Conservation Service provided soil maps and descriptions of each of the four watersheds, under a cooperative financial agreement with the project. None of the project watersheds had been surveyed for soil classification previously. About 90 days of field work were required by the Soil Scientists on the four watersheds after which the SCS Cartographic Unit in Portland, Oregon prepared the maps. The state soil scientist personally toured each watershed with the mapping scientists, and gave close supervision to the preparation of final maps and reports.

The SCS classes the surveys made on the watersheds as "medium intensity soil surveys in which strongly contrasting soils are separated and where areas of 15 acres or larger are mapped." Soil types delineated on the finished maps range in number from 12 each at Hump Creek and Lone Man Coulee to 34 at Duck Creek. The maps are all prepared on a scale of 1:20,000 (3.168 inches = 1 mile).

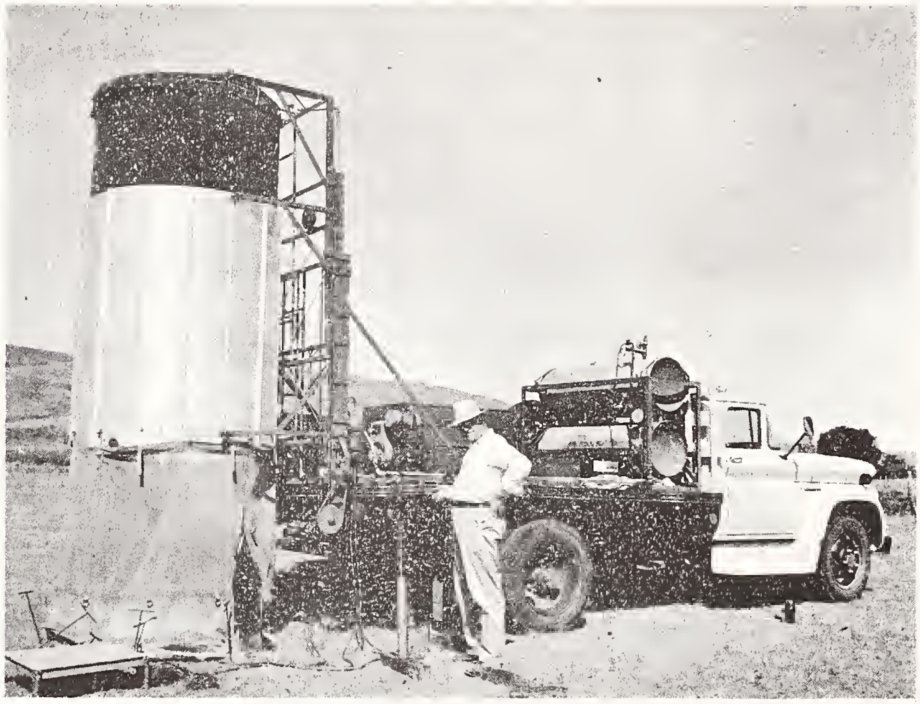
Tabulated in Appendix D are summary sheets for each watershed, showing soil types delineated, approximate extent of the watershed, and SCS hydrologic classification.

Water-Intake Studies: Infiltration capacities were determined in 1966 for the major soil types found on the project watersheds, using a "mobile raindrop applicator" which was loaned to the project by the Agricultural Research Service, USDA. This device, which is pictured in figure 25, supplies simulated rainfall at a uniform rate to a circular area of approximately 13 square feet from a height of 14 feet above the ground. Water runoff measurements are made from a two-foot square test plot located in the center of the area receiving rainfall. With this arrangement the test plot is relatively free from the influence of lateral water movement.

The raindrop applicator was developed by Mr. Frank Rauzi, Soil Scientist for the Agricultural Research Service at Laramie, Wyoming. It was made available for this project through his generosity, and the efforts of Dr. Paul Brown, Soil Scientist, ARS, Bozeman. Rauzi has published several articles describing his results with the raindrop applicator on Northern Plains watersheds. His procedures and methods were discussed in a 1960 article.

Test runs of 60 minute duration were made at each of 69 locations on the four watersheds. The Soil Conservation Service soil scientist assigned to each watershed was consulted as to the most representative locations of the various soil types and infiltration tests were made at the locations suggested by this scientist. At least two tests were made at each site, to check reproducibility. Tests were also made near each of the eight weather station installations.

Mobile Raindrop



PICTURED is a mobile raindrop applicator used to determine water intake rates on r a n g e l a n d s. Water-intake studies, using this machine, show the effectiveness of different kinds and amounts of vegetative cover ans soils on different range sites.

FIGURE 25 -- Mobile Raindrop Applicator.

A test consisted of applying rain at the rate of three inches per hour, with run-off from the test plot being recorded at five minute intervals. Water intake was measured as the difference between applied rainfall and measured runoff.

Soil samples for moisture determination of the 0-6 and 6-12 inch soil depth were taken near each test plot immediately prior to, immediately after, and 24 hours after each test. Percentage soil moisture was determined for each sample.

All standing vegetation and mulch material in the test plots were clipped at ground level after the tests, and air-dry weights determined.

Depth of penetration of water was determined at each test plot immediately after a test, and again 24 hours afterward.

Water intake rates were plotted as function of time since start of test. Summary sheets for each watershed are in Appendix D .

HYDROLOGIC INSTRUMENTATION

During the summer of 1963 recording and non-recording raingages were installed at selected ranches on each watershed, and water level recorders were placed in the stream near each USGS crest-stage gage. All the raingages were built to U.S. Weather Bureau specifications, and were installed in accordance with their suggestions. Shelters and stilling wells for the water level recorders were made from designs adapted from U.S.G.S. drawings. Details of design and installation were included in Interim Report #2.

(Williams, 1965b). A view of one of the water level recorder installations is shown in Figure 26 .

Weather station instrument packages were developed by the Electronics Research Laboratory at Montana State University, and eight of these units were installed at ranches on the watersheds during the summer of 1964. Each package consists of a group of sensors to measure wind speed, wind direction, air temperature, soil temperature and soil moisture; semi-automatic recorder to record a signal from each sensor once every 30 minutes; and cable strung underground to connect the sensors to the recorder.

At each ranch the sensors were located in a fenced enclosure 10 ft X 10 ft square, situated between 200 and 500 feet from the ranch house. Wind speed and direction were measured by a cup anemometer and single-tail direction vane built by the Belfort Instrument Company. The wind instruments were mounted atop a pole 16 feet above the ground. Air and soil temperatures were measured by thermistors made by the Yellow Springs Instrument Company. The air thermistors were mounted between two aluminum discs to permit free air movement and to obtain the proper radiation environment, while the soil thermistors were encapsulated in epoxy for protection. Soil moisture was measured by gypsum soil blocks until 1967, and after that time by plastic Bouyoucos blocks. Either style of block contains two electrodes to which alternating voltage is applied, the resulting current being a function of the moisture in the surrounding soil.

Considerable electronic circuitry was required to convert the outputs from the various sensors into a form suitable for recording. The electronic equipment and single-channel Rustrak recorder were housed in a

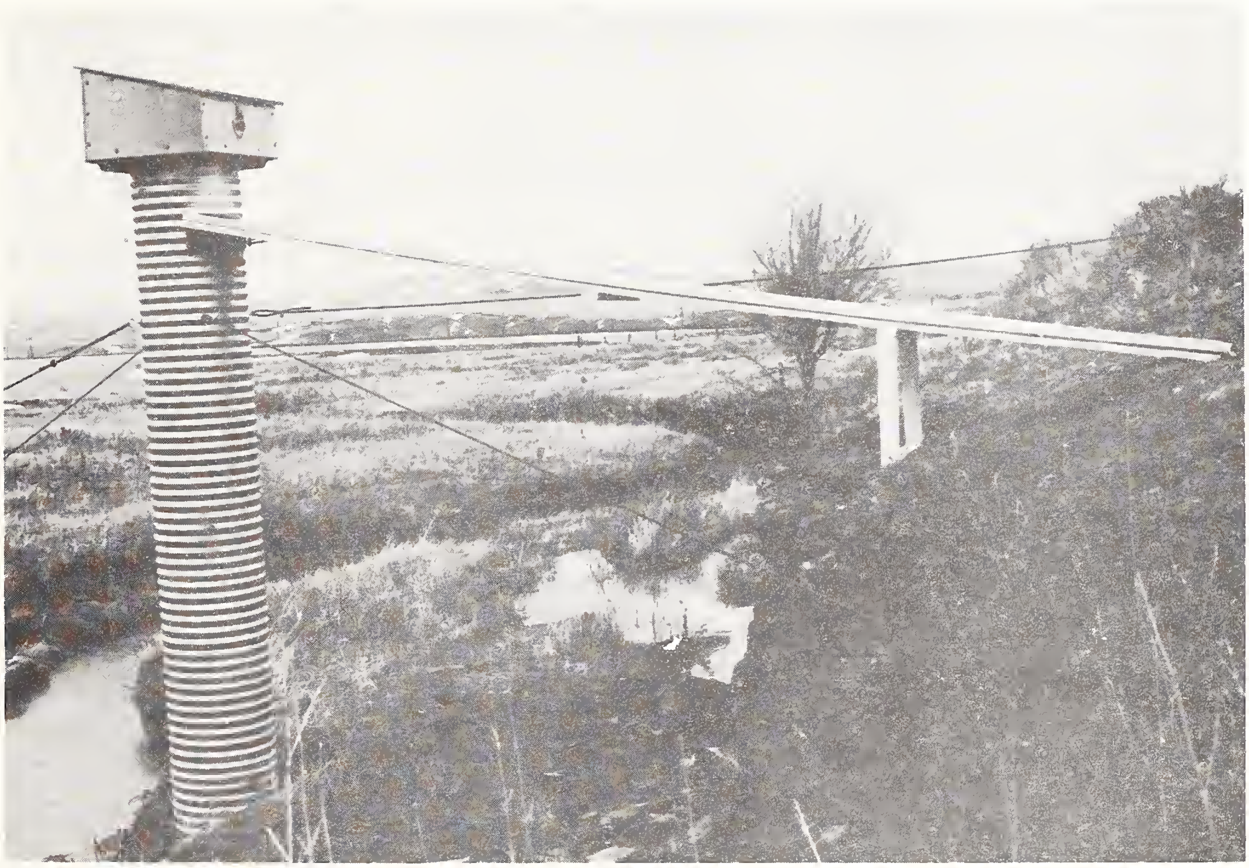


FIGURE 26 -- Water Level Recorder Installation.

metal cabinet about 18 inches by 10 inches by 10 inches. The cabinet was placed in the rancher's house, usually in a basement or storeroom. The system was designed to provide one recording from each of ten sensors at 30-minute intervals. An interval timer was used to start and stop the station automatically while a gold-plated telephone type stepper switch was provided to automatically switch (commutate) the output from each sensor in turn into the recorder.

Output from the Rustrak recorder is a 2.5-inch-wide pressure sensitive paper tape. Since the recorder was only in operation for a short time every 30 minutes, a roll of paper tape lasted for one month. The outputs from ten sensors appeared as a series of short marks on the tape, with about one inch of tape being used every 30 minutes. Identification of the outputs on the tape was possible because the wind speed which was always the first channel of the output, produced a slanting mark across the tape, while the other instruments all produced longitudinal marks and always recorded in the same sequence. A recording timer in the circuitry caused the recording time to be doubled once every 24 hours, so the midnight recording appeared as a series of elongated markes. A sample of recorder output, and the calibration code, are shown in Figure 27 .

Details of the design and installation of the weather station packages were given in Interim Report #3 (Williams and Edwards, 1965).

Figures 28 and 29 show one of the weather station sensor enclosures, and one of the recorder units.

SAMPLE OF RUSTRAK RECORDER CHART AND CALIBRATION SCALES

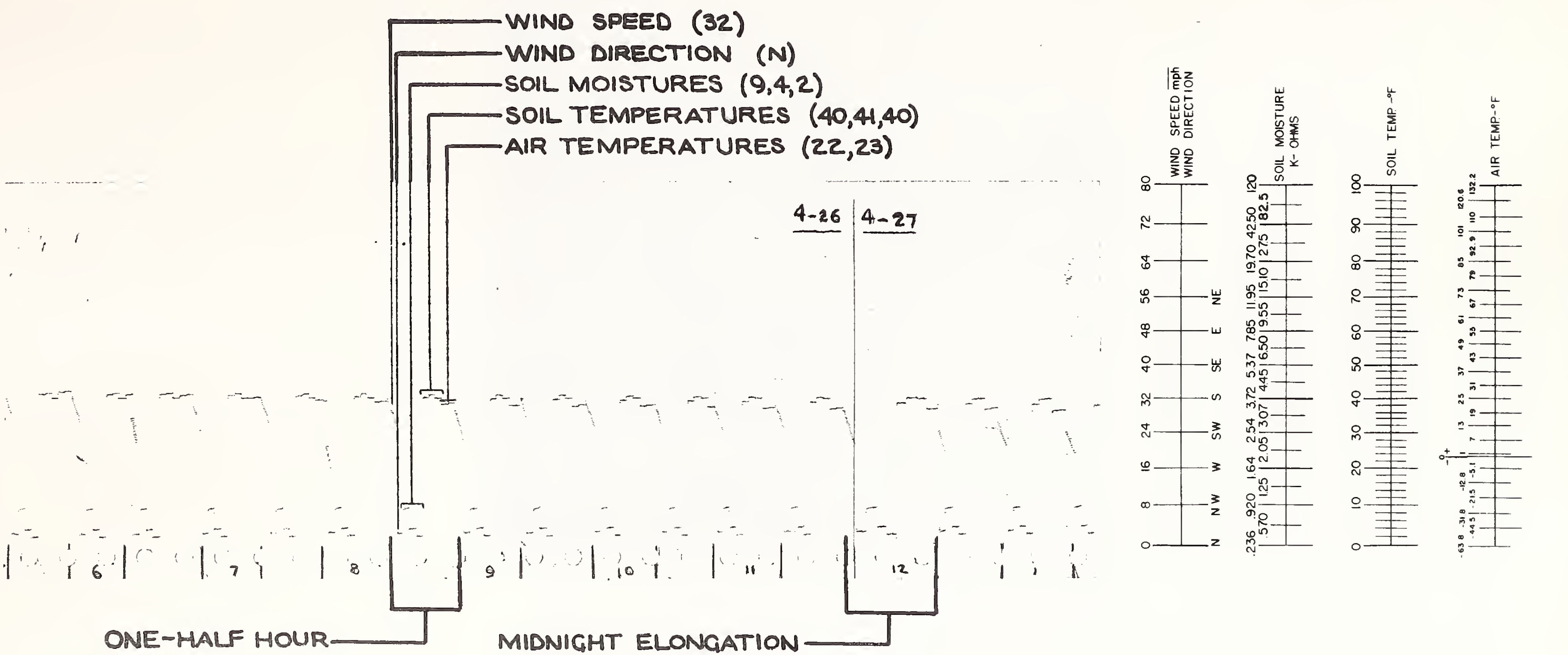


FIGURE 27

FIGURE 28 -- Weather Station Sensor Enclosure.

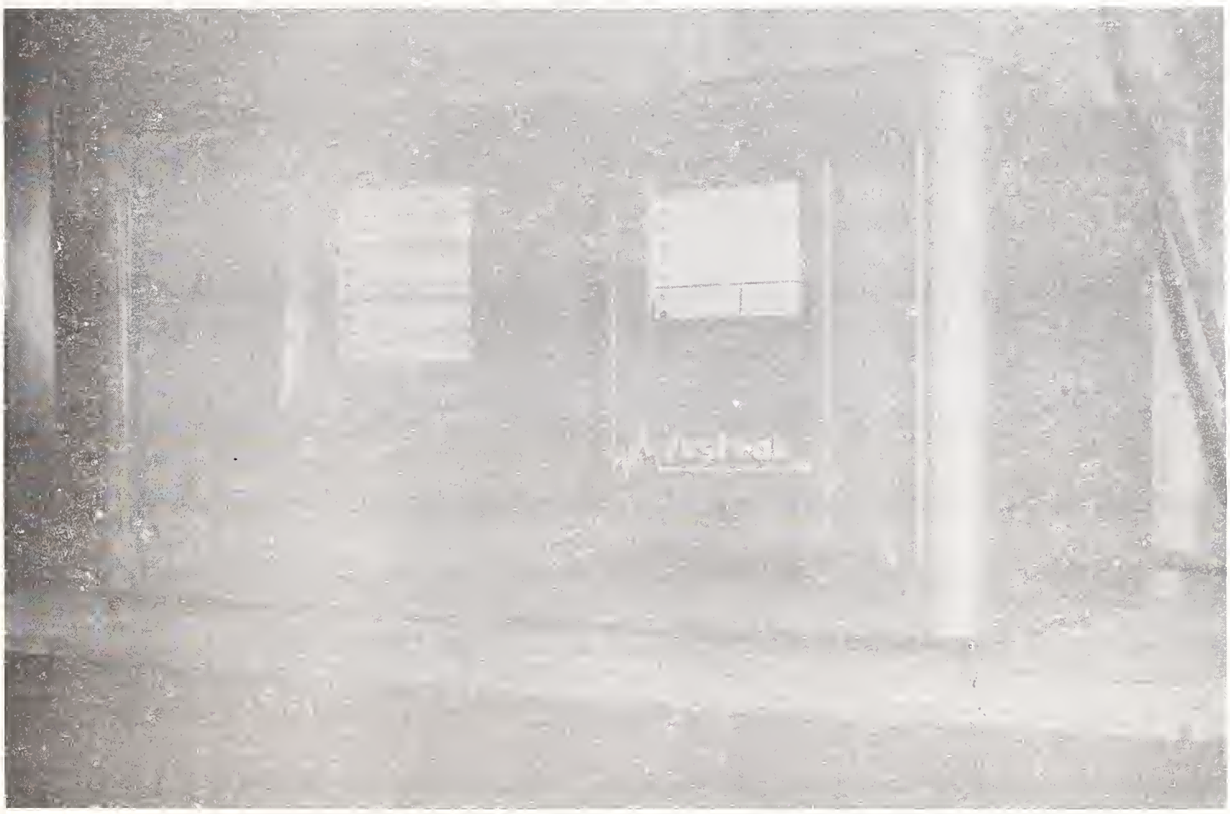


FIGURE 29 -- Weather Station Recorder, first version.

Several operational problems arose with the recording equipment, and in 1967 the Electronics Research Laboratory made extensive modifications to improve reliability and accuracy. Because additional components were added, larger cabinets, 24 inches by 12 inches by 18 inches, were required.

Figure 30 shows one of the rebuilt recorder units.

As originally installed only four of the weather stations were equipped to measure wind speed and direction. In 1967 wind equipment was added to the four remaining stations.

Data Recording

Arrangements were made with each of the ranchers where instruments were installed, for them to change charts on the instruments, wind clocks, etc. Non-recording raingages required daily inspection and measurement of contents; recording raingages required weekly inspection, clock winding and chart removal, and occasional emptying of the bucket; weather stations required monthly chart removal, and periodic inspection to see that the instrument was operating satisfactorily. Ranchers were paid a nominal fee annually for their services.

A cooperative agreement was made with the U.S. Geological Survey whereby the USGS engineers regularly inspected the water level recorders, wound clocks, changed charts and performed maintenance service as required. The USGS visits coincided with their inspection of the crest-stage gages so that extra trips were not necessary. The USGS also made current meter measurements when possible to improve their established stage-discharge relationships. Check levels were run by the USGS to each recorder installation annually.

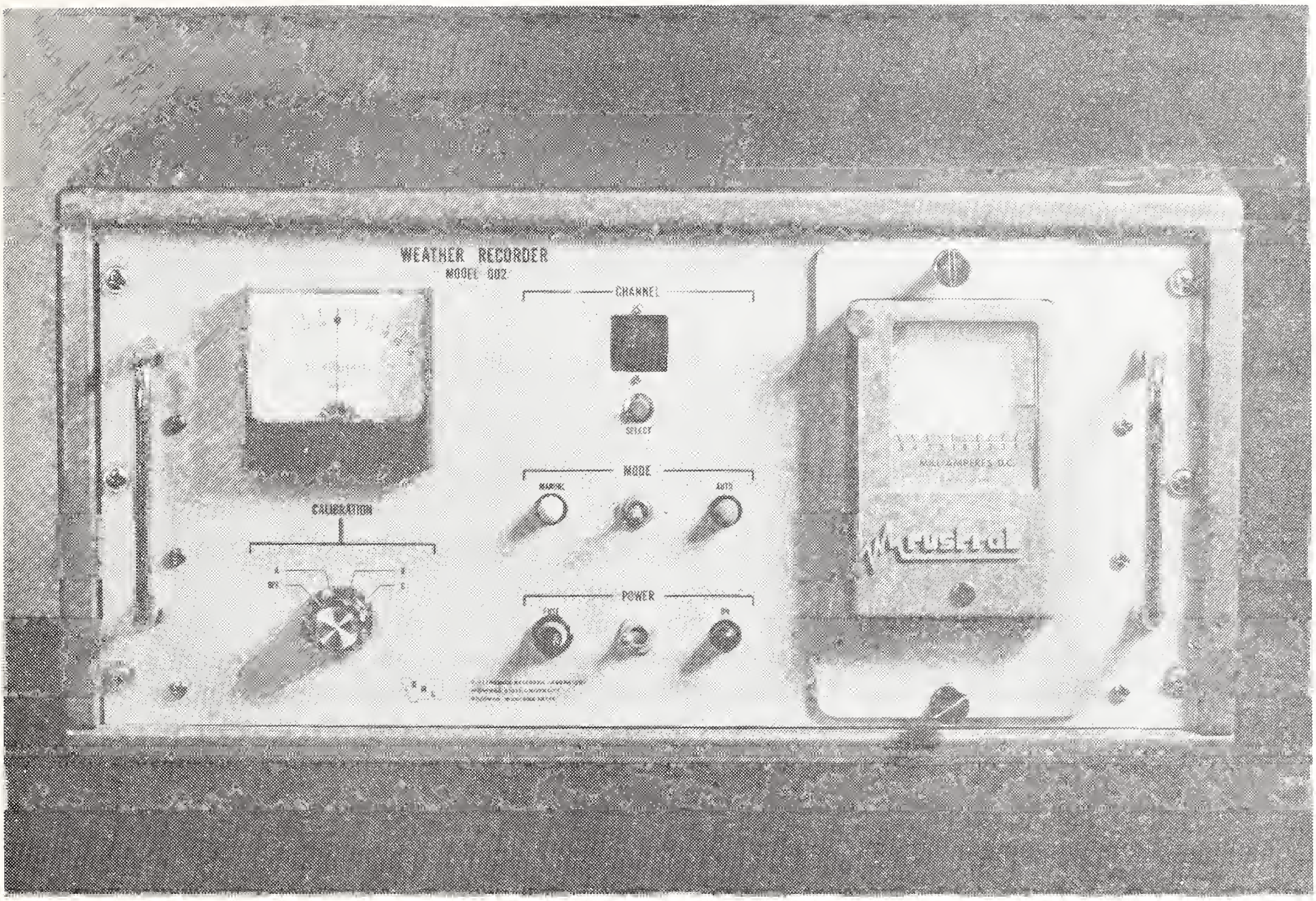


FIGURE 30 -- Rebuilt Weather Station Recorder.

Table II shows the extent of installation on each of the watersheds.

TABLE II

	Area in sq. mi.	Recording Rain Gages	Non-recording Rain Gages	Weather Stations*	Water Level Recorders
Bacon Creek	18.0	2	3	2	1
Duck Creek	53.8	3	4	3	2
Hump Creek	7.6	1	1	1	1
Lone Man Coulee	14.6	2	2	2	1

*Each weather station equipped to measure soil temperature and soil moisture at three soil depths; air temperature at two elevations; wind speed and wind direction. (Wind measurements were omitted from 4 of the stations when originally installed; wind was added to these four stations in 1967)

A brief summary of the hydrologic data gathered is presented in Appendix E.

SNOW STUDIES

Two techniques were employed for evaluating snow melt potential on the watersheds. These were periodic snow surveys, and aerial photos.

The State Snow Survey Supervisor, U.S. Soil Conservation Service aided in the establishment of three snow survey stations on each of the four watersheds. SCS personnel from the local work units then made surveys within a few days after each snowstorm of six inches or more. At each of the three locations the surveyor collected 10 samples with a two-inch core sampling tube, recording snow depths and core weights. The core weights were then converted into inches of water.

Summary snow survey data are shown in Appendix E .

Aerial photographs were taken by the Montana Highway Department photography section from the department's Aero-Commander. It had been hoped that flights could be made after each major storm to evaluate the effect of drifting. Weather conditions and scheduling problems prevented the obtaining of photographs as frequently as desired, but one set was obtained for each watershed in February or March of 1964, 1965, 1966, 1967 and 1968. These photos were used qualitatively to estimate percentage of watershed that was snow covered. Although the quality of the photos would permit stereoscopic viewing, no estimates of snow depths were made.

ASSESSMENT OF EFFECTIVENESS OF HYDROLOGIC DATA COLLECTION

Precipitation and streamflow data were collected on the four watersheds for six years, from September 1963 to September 1969. Supplemental data were collected on three of the watersheds from April to June 1970. Additional meteorological information (wind speed and direction, air and soil temperature, soil moisture) was obtained between July 1964 and September 1969. Some comments regarding effectiveness of the data collection program follow.

Precipitation Data

There were relatively few gaps in data at most stations during the six years. One rancher-observer at Hump Creek, where a recording raingage was established, was frequently absent from the ranch for extended periods, and the 8-day clock on his raingage was often allowed to run down. This station had more missing records than any other.

Reliability of the precipitation data is felt to be generally very good when the precipitation fell as rain, and fair to poor when it fell as snow. Snow on these watersheds is almost always accompanied by wind of varying intensities, and the precipitation caught by the raingages under such conditions is often as low as 50 percent of the true precipitation.

The efficiency of the raingages during winter months could perhaps have been improved by the addition of windshields. The decision to omit windshields was based on economics, and the result of conversations with several researchers at MSU who generally reported that the use of windshields had apparently been only partially effective in their studies.

Streamflow Data

Streamflow records obtained for the four watersheds are believed to be very good. The only major missing data is from the Duck Creek station for 1963-64. The Duck Creek stilling well and recorder were originally attached to a county bridge over Duck Creek; but the bridge was so light that traffic caused serious vibrations and made recorder operation unfeasable. In 1964 the recorder was relocated away from the bridge and no further difficulties were encountered.

During winter months the float in each of the stilling wells was suspended out of the water to prevent freezing, in such a way as to float free when the water level rose; it is believed only very minor streamflow events were missed.

There were long periods at each of the stations with no flow, or almost no flow. Gaging operations might have been more efficient had modifications

been made to the recorders to prevent them from running until the water level rose. An attachment for this purpose is available, and causes a recorder to sit idle until streamflow occurs, at which time it commences operation and runs until an inspector stops it after the streamflow ceases.

Weather Station Packages

The weather station packages were developed at Montana State University because comparable equipment was not available commercially at prices the Project could afford. The equipment as developed provided a maximum amount of meteorological data for the price; however, compromises were necessary, and several problems arose as a result. Although operation was improved when the electronic packages were rebuilt in 1967, some of the problems never were eliminated entirely.

Changing charts on the Rustrak recorder is an intricate process which must be done very carefully if the recorder is to operate properly. The chart drive operates through a friction clutch, and unless the chart is installed perfectly, it will not advance. The rancher-observers on the project had considerable difficulty with the charts.

When the units were rebuilt in 1967 the recorders were installed so they could be removed by unplugging. Two spare recorders were purchased so a rancher could unplug one, mail it to the project supervisor, and install another recorder on which the charts was already installed. For a time the recorders were mailed back and forth regularly, but the operation did not prove to be much more reliable even with "experts" installing the charts.

Occasional power failures at the ranches caused the stations to be out of operation for varying periods. This caused the "midnight elongation" of the output to be generated at the wrong time, until the observer re-set a timer on the unit. This problem was alleviated in 1967 when the timer was converted to flashlight battery power.

With the exception of soil moisture elements, very few problems were encountered with the sensors situated in the instrument enclosures. Both types of soil moisture block used (gypsum and Bouyoucos) operate by measuring current between two electrodes embedded in the element in the presence of alternating voltage. The current varies with moisture tension in the soil, and the tension is in turn related to the moisture content. The blocks were calibrated to establish a current-tension relationship for each, and soil samples from each of the installation sites were tested to determine tension-moisture relationships. The gypsum blocks, which were originally installed, were thought be be superior for use in some Montana soils which are high in salt content; some of these blocks deteriorated rapidly (probably owing to freeze-thaw conditions) so they were all replaced in 1967 by the more durable Bouyoucos blocks.

Calibration of the soil moisture elements was never entirely satisfactory; soil moisture data, therefore, should be used qualitatively only, to establish periods of relatively wet or relatively dry soil, and not to evaluate precisely the soil moisture conditions.

The output records from the Rustrak recorders were converted into digital form by manual-visual means. A minimum of 8 man-hours of student

labor was required for the reduction of data from one chart. Inexperienced students took up to twice that amount of time.

SUMMARY

The procedures followed in the hydrologic studies of four small watersheds have been described. Data collection and reduction problems have been discussed. Summaries of watershed characteristics, and hydrologic data gather are presented in Appendices B, C, D and E.

CHAPTER IV

THE 1964 FLOOD AT LONE MAN COULEE

On June 7-8, 1964 a rain storm of unprecedented magnitude and areal extent struck a wide area of north-central and northwestern Montana. The storm, which was centered over the continental divide, resulted in floods much larger than any which had ever been recorded on many watersheds. Lone Man Coulee, in Pondera County is located about 50 miles east of the storm center, but it received over 5 inches of rain during the 30-hour storm. The resulting hydrograph had a peak flow of 1740 cfs and total runoff of 1.67 inches. The watershed had been selected in 1963 as one of the Project watersheds to be studied comprehensively in this investigation, and during the 1964 storm four raingages (two recording and two non-recording) and one continuous recording water level recorder were in operation.

The Project supervisor visited the watershed on June 8, 1964, and took a number of pictures at the mouth of the stream shortly before the failure of a six-foot culvert under a county road. See Figures 31 to 34.

Project personnel returned to the watershed a week after the flood, flagged high-water marks, and conducted a slope-area study to determine discharge peak.

The hydrology of Lone Man Coulee was studied in detail using data from the June 1964 flood and other runoff events which occurred in 1964 and 1965. Two reports of findings were prepared (Williams, 1964 and Williams, Robinson and Hanson, 1966).

Lone Man Coulee - Upstream Overall View from Left Bank 6/18/64

Lone Man Coulee - WS Recorder and Culvert Fill(Note Man Crossing Fill) 6/ 8/64

FIGURE 31.

Lone Man Coulee - Across Channel from Left Bank

6/18/64

Downstream Overall View of Lone Man Reach

6/18/64

FIGURE 32.

Lone Man Coulee - Looking Upstream from Bluff above Culvert (Miller Coulee from Right) 6/ 8/64

Upstream at Lone Man Coulee (Confluence with Miller Hidden by Rocks)

FIGURE 33.

Lone Man Coulee - Flooding Culvert Upstream from
WS Recorder and Culvert Fill 6/ 8/64

Lone Man Coulee - Looking Downstream at WS Recorder
and Culvert Fill 6/18/64

FIGURE 34.

CHAPTER V

MULTIVARIATE STATISTICAL STUDIES

Principal component analysis and varimax rotation of the principal factors, using watershed characteristics and hydrologic data determined for the four project watersheds, were performed to provide information about the relative importance of 29 independent variables to the peak discharge rates and runoff volumes produced by these variables. A series of computer programs was written to perform the various operations. Data from 50 runoff events were used, twenty of which were snowmelt, and 30 were rain-caused.

The procudures are described briefly in this chapter, and the results are discussed. The procedures and the reasons for their selection, together with theoretical background material were presented in detail in Interim Report #6 (Lewis and Williams, 1968). Since publication of that report further analysis has been made using the same data, and a computer error which causes slight changes in the results, has been corrected.

REVIEW OF PROCEDURES

Five watersheds were considered (East Duck Creek and Duck Creek were treated as separate watersheds because they were each equipped with a water level recorder). Twelve watershed parameters each of which were assumed to remain constant with time, were determined for each basin. Field measurements, as well as map and aerial photograph analysis were employed. In some cases weighted mean values were used.

Seventeen storm variables were determined for each of fifty runoff events which occurred on the five watersheds during the years 1964-67.

Descriptions of the 29 parameters and tabulated values for each are shown in Appendix F .

The amount and type of data available suggested that a principal component extraction, followed by a varimax rotation for interpretation of the variables, and a multiple regression on either the principal components or the rotated factors for the prediction equation would represent the best statistical system of analysis. (See Lewis and Williams, 1968, for comments of various investigators proposing these methods).

The various steps required in the study are shown in block diagram form in Figure 35 , and are described below. Each step is a computer program solved sequentially, each utilizing the results of preceding steps.

Correlation is a program to compute means, standard deviations, variances and co-variances, sums of squares, and correlation coefficients of any number of observations for up to 32 different variables or parameters. (See Lewis & Williams, 1968, Appendix E).

Principal Components Analysis is a program which performs a principal component analysis on a correlation matrix (up to 60 X 60) and produces up to 60 normalized eigenvectors and the respective eigenvalues of each factor. The principal factors are also computed. The variance (eigenvalue) of each vector, percent of variance explained by each factor, and accumulated percent are also computed. (See Lewis & Williams, 1968, Appendix F).

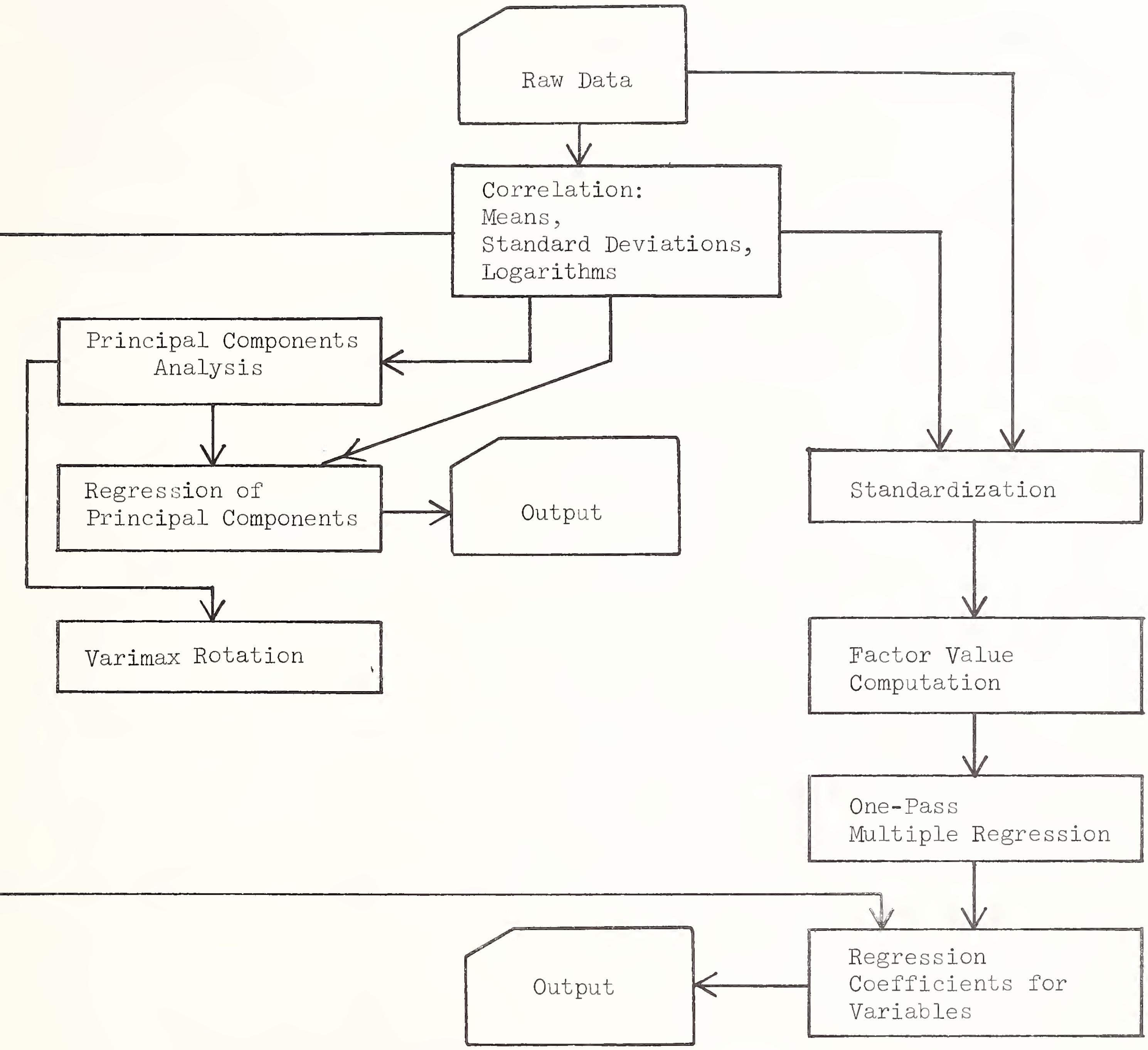


FIGURE 35 -- Block Diagram of Multivariate Procedures

Regression of Principal Components is a program which computes principal-component regression coefficients for the eigenvectors.

Varimax Rotation is a program to perform an orthogonal normal varimax rotation of as many as 75 factors with loadings for as many as 100 variables. Variances, percents and accumulated percents of the final rotated factors are also computed. (See Lewis and Williams, 1968, Appendix G)

Standardization is a program which computes the standardized form of 31 variables from the observations, variable means and variable standard deviations. The new values are dimensionless, have a mean of zero, and a standard deviation of unity.

Factor Value Computation is a program which computes the values of up to 10 factors using data from up to 50 observations of as many as 31 variables. The operator selects which of the 31 variables are important and are to be used in the factor equations, by studying the output from the varimax rotation program.

One-Pass Multiple Regression is a program which computes means, variances, standard deviations and all pairs of correlations for as many as 30 variables. Any one of the given set can be selected as the dependent variable, with any sub-set of the remaining variables used as the independent variables.

Regression Coefficients for Variables is a program which converts the regression coefficients for factors into coefficients for the variables contained in the factors.

RESULTS

The principal component analysis resulted in the generation of exponents B_1, B_2, B_3, etc. in the equation,

$$Y = B_o X_1^{B_1} X_2^{B_2} X_3^{B_3} \ldots X_{29}^{B_{29}} \tag{8}$$

and the constant B_o. In this equation Y is the dependent variable (peak discharge rate or total runoff volume) and X_1, X_2, X_3, etc. are values of the 29 watershed parameters and storm variables. Table III (a) presents the applicable exponents and constant for the analysis using all 50 events, and also for a later analysis using the 30 events that were rain-caused. (With the 30 events snow water equivalent was omitted, leaving 28 variables). In examining Table III it should be noted that negative signs imply inverse correlation; i.e., peak discharge rate varies inversely with FREQ (stream frequency) and directly with ELEV (watershed elevation). The principal component analysis does not provide information as to the relative importance of each independent variable.

The purpose of the varimax rotation was to "rotate each of the principal components" so that each component would have high coefficients on certain variables and low coefficients on the other variables, thereby allowing interpretations for the important variables. Using data from all 50 events, varimax rotation classified the 29 independent variables into ten

TABLE III: Results of Multivariate Statistical Studies.

	a) Principal Component Regression				b) Factor Regression			
	30 Events		50 Events		30 Events		50 Events	
	QMAX	RUNF	QMAX	RUNF	QMAX	RUNF	QMAX	RUNF
A	.179051	.001300	.064826	-.243972	.041976	-.148567	.179966	-.202529
SHP	-.106416	-.530779	.071485	-.202842	-.386962	-.926787	.182572	-.110884
AZ	.584909	.299468	.356148	-.017989	.541161	.200852	.305262	-.254702
ELEV	.575577	.356734	.386138	.008814	.460789	.245002	.157598	-.331776
GNDS	-.249696	-.121176	-.164463	-.017034	-.249912	-.085730	-.150769	-.089726
GNDL	.379861	.202998	.202876	-.039809				
FREQ	-.049132	-.175176	-.054731	-.192630	-.262955	-.374446	-.042866	-.138148
L	.140138	-.118485	.032794	-.312441	-.074535	-.359196		
S	-.083684	-.038010	-.119327	-.140687	-.247380	-.130541	-.281397	-.183205
USE	.001539	-.063571	-.013586	-.094326	-.094787	-.154893	-.011322	-.078904
INFR	-2.843262	-.129365	-3.337532	-.146259	-2.206426	1.132616	-3.699747	.841672
POND	.018874	-.008000	.032370	.025224	.040526	-.005795	.054937	.023206
I	.145833	-.056228	.085395	-.006565	.503561	.113576	.288065	.042956
ISD	.192799	.027532	.043605	-.015621			-.091556	-.351056
D	.393892	.526396	.068394	.204391				
TDF	-.068341	-.075371	-.047378	-.049490				
TPCP	.578529	.766306	.184478	.324823	1.353580	1.607936	.458162	.906049
API	.124291	.315562	.030107	.221600	-.130018	.107360		
SOLM	.180608	.297635	-.322610	-.098856				
WDIR	-.288083	-.157852	-.003508	.276440				
WEEK	.932895	.743919	.136083	.159539	-3.561336	-3.312721	-.829548	-.295143
AIRT	.252005	.221283	-.088364	-.172060	-4.050199	-3.472219	.376330	.874686
ATSD	.468769	.645473	-.248434	-.173777				
WVEL	.089614	.040077	.367852	.519173				
WVSD	-.660410	-1.245454	-.373373	-.903024				
SOLT	1.346793	1.256378	.067019	-.054305			-.142306	-.499087
STSD	.133659	-.087366	.120227	.188553	.358391	.417306		
DEGD	1.574651	1.481928	-.082601	-.293026	8.945935	7.571302	-.698326	-1.633904
SWEQ			-.013572	-.007077			-.050824	-.052257
Constant	-12.458941	-9.712135	-3.776739	.189079	-7.797616	-3.596356	-2.180520	3.823367

Note: Parameters are identified in Appendix F.

groups or "factors" and indicated which variables were relatively more important to each factor. Also, each factor is relatively less important than the preceding factors. The same procedure was followed for the 30 rain-caused events, classifying the 28 independent variables into 11 factors. The varimax rotation results are shown in Table IV . The variables deemed to be most important are shown in the shaded areas of the table.

Following varimax rotation and perusal of Table IV , any desired combination of variables can be used in factor value computation and regression analysis. This was done with 18 selected variables and all 50 events, and again with the 30 rain-caused events. As with principal component analysis the result is generation of exponents B_1, B_2, B_3, etc. and the constant B_o in equation 8. Table III (b) shows the results of this analysis. As before, the sign of each exponent is more significant than its magnitude.

After publication of Interim Report #6 (Lewis and Williams, 1968) a computer programming error in the factor value computation program was detected, and this is responsible for slight errors in Table XI (page 74) of that report.

DISCUSSION OF RESULTS

A search of literature failed to show that the techniques used in this phase of the investigation had been used before for hydrologic studies as large as this one. These techniques are much more useful than ordinary regression methods for two reasons. First, it is presupposed in a

TABLE IV: Successive Importance of Variables to Factors.

a) Fifty Events

Factor	Decreasing Order of Importance →						
1	SOLT	I	ISD	AIRT	SWEQ	WEEK	DEGD	D
2	AZ	GNDS	ELEV	INFR	SOLM			
3	SHP	USE	FREQ	GNDL	STSD			
4	POND	S						
5	A	L						
6	WVSD	WVEL						
7	TPCP	API						
8	ATSD							
9	TDF							
10	WDIR							

b) Thirty Rain-Caused Events

Factor	Decreasing Order of Importance →						
1	AZ	GNDS	ELEV	INFR	API			
2	SHP	FREQ	USE	STSD				
3	I	AIRT	ISD					
4	A	L	GNDL					
5	TPCP	D	WVEL					
6	POND	S						
7	ATSD							
8	WVSD	SOLM						
9	WDIR							
10	TDF							
11	WEEK	DEGD	SOLT					

Note: The variables deemed to be most important are shown in the shaded areas of the table.

Parameters are identified in Appendix F.

regression study that all the variables used are mutually independent. In a hydrologic study this is not a valid assumption because it cannot be stated for instance that precipitation intensity occurs completely independently of wind velocity. To the extent that the variables are inter-related, ordinary regression methods will give erroneous results. The techniques selected for this investigation have been shown mathematically to eliminate the effects of inter-correlation among the variables. Second, ordinary techniques cannot indicate the relative importance of the variables used. The varimax rotation with factor analysis employed in this study provides a means of determining which variables are most important.

Multivariate analyses were used in this investigation to see whether they offered possibilities for delineating the important parameters affecting flood peak magnitudes, as well as to determine the form of the regression equation for flood peak magnitude. Results of the study must be considered preliminary, but the objectives were met. The study showed that it is indeed possible in this manner to delineate important parameters, and it is possible to develop a regression equation for flood peak magnitude.

There are several ways in which the study could be improved upon, if it were to be done again. These include:

1. Redefine some of the variables. Precipitation intensity should be defined as the average intensity during the period of excess rainfall of the storm instead of the average intensity computed for the beginning of rainfall to end of runoff. Storm duration, defined as average time to center of area of all rainfall hydrographs for the watershed does not appear to be meaningful in terms of peak discharge magnitude, although it may

be related to total runoff volume. Total precipitation likewise is probably not meaningful in establishing peak discharge rates.

2. Provide a more dense network of instrumentation. Some parameters were based upon single or a few measurements even though they were quite variable across the watershed.

3. Include geographical factors. With the exception of watershed elevation no parameters describing geographical location within the state were included.

4. Try more combinations of parameters in the factor analysis. There may be a combination of variables that is better than the 18 used in the preparation of Table III (b) (or the 14 and 6 reported by Lewis and Williams, 1968).

Consideration of the exponents resulting from principal component as compared to factor regression on Table III shows that the maximum discharge study of 30 events, the two methods result in opposite sign of exponent on five variables, L (stream length), USE (land use ratio), API (antecedent precipitation index), WEEK (week of the year) and AIRT (air temperature). Intuitively, the sign for API seems correct on principal component regression and wrong on factor regression. (The positive sign indicates increasing peak discharge rate with increasing magnitude of API). It is not immediately evident that either sign is better for the other four exponents. Two exponents appear intuitively wrong for both methods GNDS (overland ground slope) and S (main channel slope). Discharge rate would logically vary directly with both these terms.

Examination of the listing of relative importance of variables to factors (Table IV) shows that the study has identified the obviously import-

ant parameters for the analysis of 30 events. When 50 events are considered, the effect of lumping snowmelt and rain-caused events together has masked the importance of either SOLM (soil moisture) or API (antecedent precipitation index). Certainly with rain-caused events one of these variables should be included.

Interim Report #6 (lewis and Williams, 1968) describing the multivariate statistical studies was reviewed by D. C. Woo, for the Structural and Applied Mechanics Division, Federal Highway Administration. Woo had comments on two areas: input data, and hydrological interpretation.

Regarding input data, Woo noted that no assessment of the accuracy of the recorded data was attempted. Future studies of this nature should include validity checks on the data collected. This will, however, require a greatly expanded data collection network, and hence a more costly study.

Regarding hydrological interpretation, Woo suggested that runoff events should be grouped by magnitude, and events of comparable magnitude considered separately. He further pointed out that snowmelt events should be treated apart from rain-caused events. Future studies should consider classification of events by magnitude as Woo suggests. As reported in this chapter, rain-caused events have been studied separately since publication of Interim Report #6.

CONCLUSIONS

The results of the analysis described here point to a recommendation that in the future hydrologic study of small watersheds, where peak discharge

determintation is the goal, attention should be focused to obtaining as much reliable information as possible on precipitation intensities and amounts, and air temperatures; with lessened emphasis on wind speeds and directions, and soil moisture measurements. Soil temperature measurements are important when snowmelt is considered, but unnecessary when rain-caused events only are considered.

A further recommendation is that principal component analysis be tried with a lesser number of parameters. The results of this study verify the contention of Amorocho and Hart (1964) that the use of fewer parameters is generally more successful than the use of many parameters. Reduction of the number of parameters would rule out the use of factor analysis, however, because 20 is considered the smallest number which will produce satisfactory results in such a study.

SUMMARY

This chapter has described the procedures used in multivariate statistical analysis of data from five watersheds and fifty runoff events, and has discussed the results obtained.

CHAPTER VI

STUDY OF SOIL CONSERVATION SERVICE METHOD

The U.S. Soil Conservation Service has developed several methods for determining peak flow rates from small watersheds. Some of these methods are discussed in Chapter VII of this report; but the principal method currently in use by the SCS is reviewed in this chapter, and the results of a test of the method, using data from an actual storm which occurred on Duck Creek watershed, are reported. More details are supplied in Interim Report #5 (Ferris and Williams, 1968).

SCS METHOD

In their watershed planning studies, Soil Conservation Service engineers are first interested in total runoff volume, because total volume determinations are critical in establishing the feasibility of reservoir construction and other reclamation activities. Discharge rate is of importance only insofar as it affects spillway capacities, etc. In all their hydrologic methods, therefore, determination of total runoff volume is accomplished first, using methods developed by SCS engineers. Various methods are then employed for determination of peak discharge rate; these methods usually involve standard flood routing techniques, unit hydrograph construction, or others.

None of the SCS methods assign a return frequency to the runoff volume or peak flow rate. Rather, they work from a real or hypothetical rainstorm

and although the rainstorm may be assigned a return frequency, the resulting runoff event is not.

Runoff volumes

The accumulated volume of runoff in inches depth over a drainage area which results from a design rainstorm is given by

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{9}$$

where Q is accumulated volume of runoff, P = accumulated rainfall, I_a is an initial abstraction, including surface storage, interception and infiltration prior to runoff, and S is potential maximum retention of water by the soil. Each term is measured in inches equivalent depth over the watershed.

As a result of studies of many watersheds in various parts of the United States, the SCS concluded that I_a, the initial abstraction, can be taken as 0.2S. This causes equation 9 to be reduced to

$$Q = \frac{(P - 0.2\ S)^2}{P + 0.8\ S} \tag{10}$$

The potential maximum retention term, S, is usually replaced by an expression involving a curve number, CN, given by

$$CN = \frac{1000}{10 + S} \tag{11}$$

The curve number CN is a function of soil type, land use, vegetative cover, soil temperature, antecedent moisture conditions, and other hydrologic soil characteristics. With CN determined, equation 9 may be solved algebraically, or graphically by use of figure 36.

The most important factor affecting CN is the soil type. The SCS has classified more than 4,000 agricultural soils in the United States into one of 4 hydrologic soil groups, A,B,C, or D. Soils in group A are highly permeable and have low runoff potential. Soils classified in group D are nearly impermeable and have high runoff potential. The SCS has developed extensive tables which incorporate land use, conservation treatment, hydrologic condition and hydrologic soils group, assigning a curve number, CN, to each combination. Antecedent moisture conditions are accounted for by arbitrarily increasing the CN if conditions are abnormally wet, and lowering it if conditions are especially dry. Since most watersheds include several different soil types and/or land use practies, a curve number is established for each subsection of the watershed, and a composite or weighted CN is determined for the basin as a whole by prorating the areas of all the subsections.

Peak Discharges from Basins Under 2000 Acres

For drainage areas of 5 to 2000 acres the SCS has prepared charts showing peak discharge as a function of drainage area, curve number, watershed slope, geographical region and 24-hour rainfall depth. Separate charts were prepared for each curve number, for watershed land slopes of 1%, 4%, and 16%, and for two geographical regions. If a given watershed has a

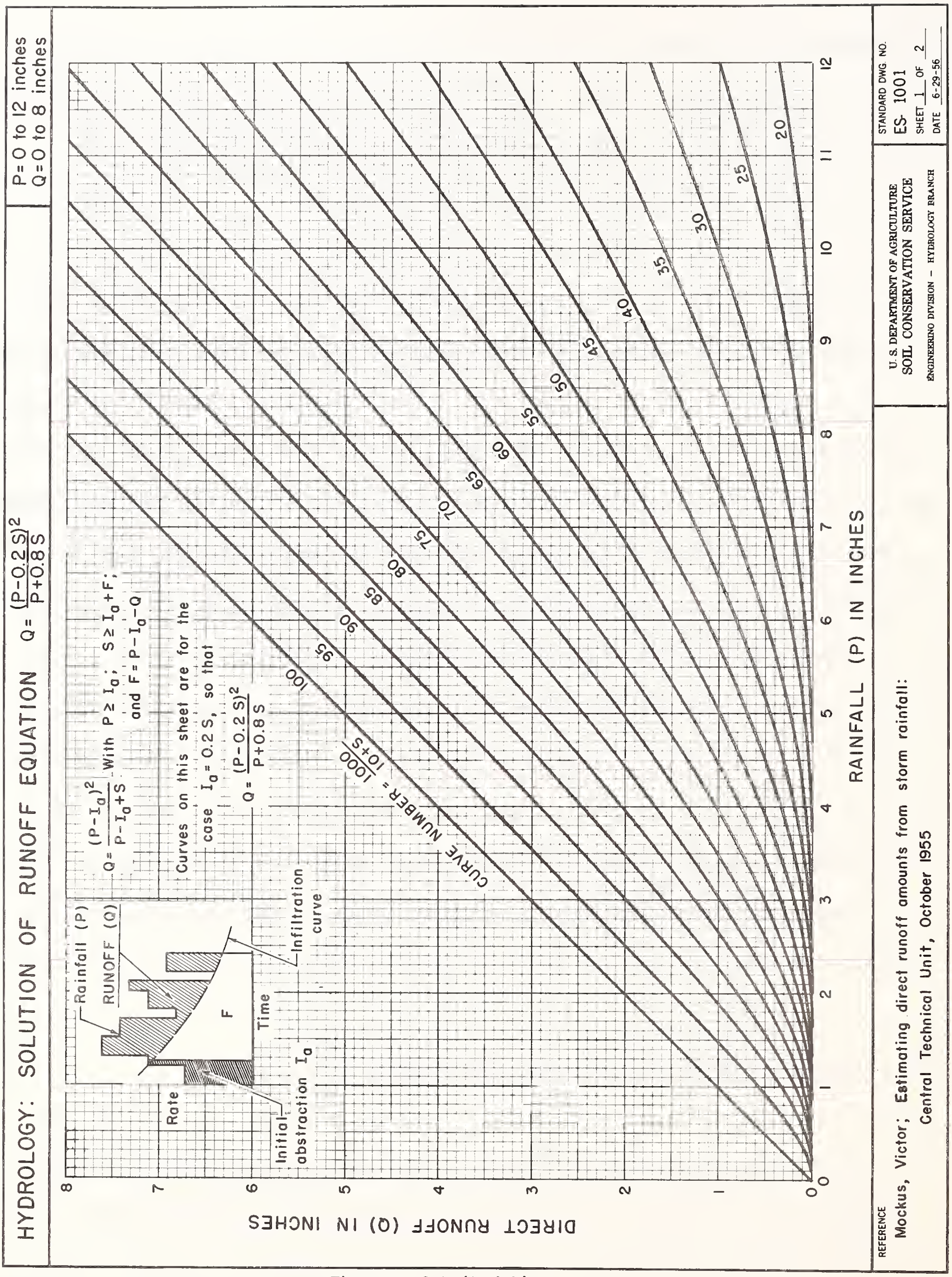


Figure - 10.1 (1 of 2)

FIGURE 36 -- Soil Conservation Service - Solution of Runoff Equation

different slope, straight line interpolation is permitted using logarithmic graph paper. Type 1 geographical region is considered typical of maritime climates and coastal areas of the United States and Type 2 considered typical of continental climates with intense summer rainstorms. ESSA publications are used to determine the rainfall depth corresponding to a 24-hour duration and any desired storm frequency. Figure 37 shows the chart for curve number 75, 4% (moderate) slope, and Type II storms.

Peak Discharge from Gaged Basins

When a basin under study has streamflow records available, for which unit hydrographs can be developed, the SCS uses these together with runoff volumes determined for design storms, in predicting peak discharge rates. Base flow and snowmelt discharge, if necessary, are added to the discharge determined from the unit hydrograph.

Peak Discharge from Ungaged Basins Using Normalized Unit Hydrographs

The SCS has developed 112 "normalized" unit hydrographs which may be used with ungaged watersheds. The 112 unit hydrographs apply to drainage areas having times of concentration varying from 1.5 hours to 72 hours. Selection of which unit hydrograph to use is based upon time of concentration and upon the ratio of accumulative runoff at the end of one day divided by total accumulated runoff at the end of ten days, Q_1/Q_{10}. Time of concentration, T_c, for the drainage area is determined as longest time of bank-full channel flow plus overland flow time. The direct runoff for one day and for ten days are estimated using appropriate curve number (CN) values, and these

PEAK RATES OF DISCHARGE FOR SMALL WATERSHEDS
TYPE II STORM DISTRIBUTION

SLOPES – MODERATE
CURVE NUMBER – 75

24 HOUR RAINFALL FROM US WB TP-40

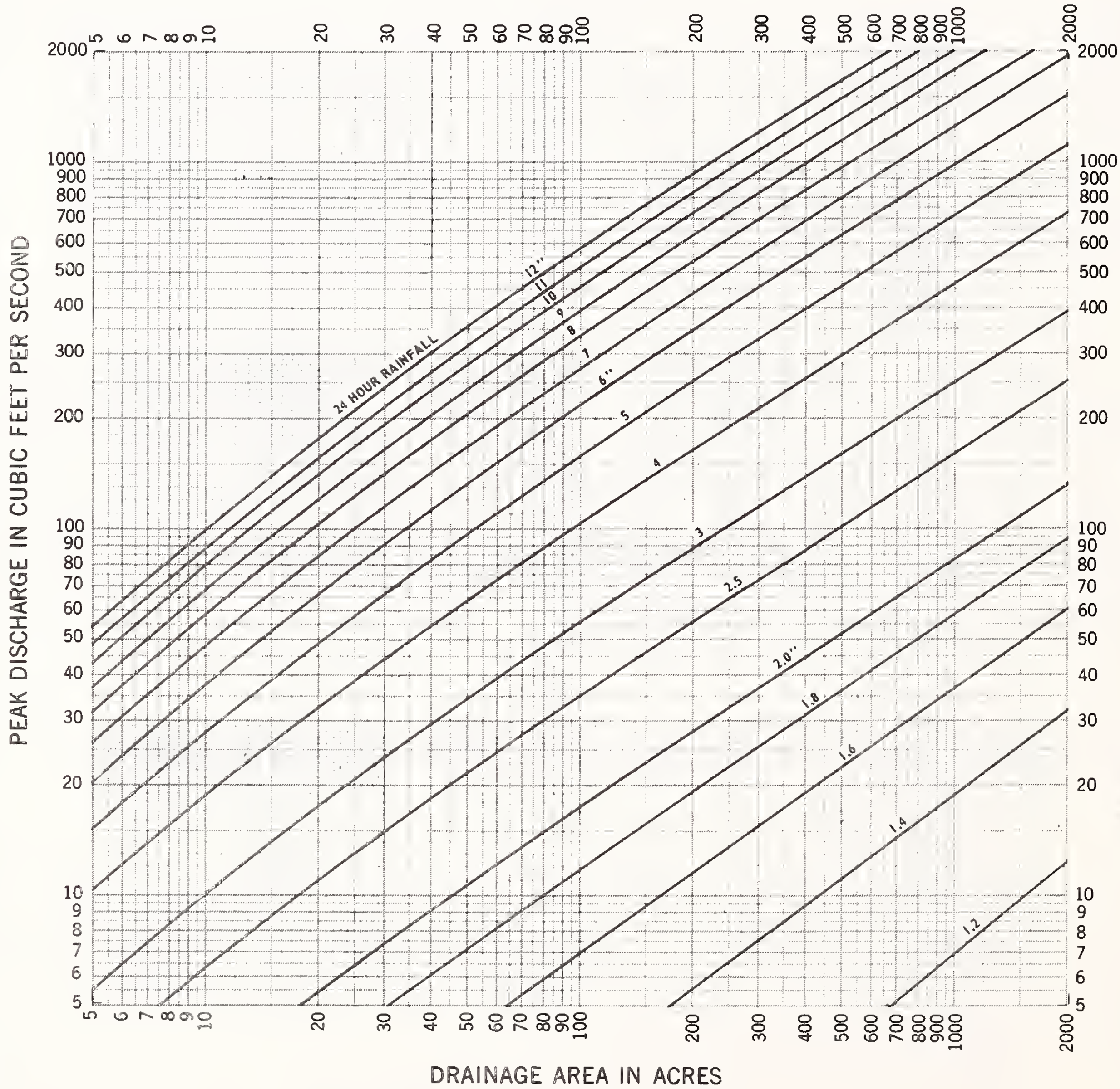


Exhibit 2-9

REFERENCE	U. S. DEPARTMENT OF AGRICULTURE SOIL CONSERVATION SERVICE ENGINEERING DIVISION - HYDROLOGY BRANCH	STANDARD DWG. NO. ES- 1027 SHEET 11 OF 21 DATE 4-1-66

FIGURE 37 --Soil Conservation Service - Peak Rates of Discharge for Small Watersheds. Type II Storm Distribution.

estimates are reduced if the watershed area exceeds 10 square miles (areal rainfall is less that point rainfall), and if channel losses are significant. Channel losses are significant if the stream is influent. A so-called "climatic index," Ci, is computed from the equation

$$Ci = \frac{100\ P_a}{(T_a)^2} \qquad (12)$$

where P_a = average annual precipitation in inches

T_a = average annual temperature in degress F.

If the watershed has a climatic index less than 1.00 the stream is considered influent, and channel losses are subtracted from direct runoff according to tables prepared by the SCS.

With the Q_1/Q_{10} ratio and T_c value established, the serial number of the appropriate unit hydrograph is obtained from a table. The peak discharge is determined as the maximum value of the normalized unit hydrograph multiplied by drainage area (in square miles) and by Q_{10} (in inches). Baseflow and steady-state snowmelt rates are added if necessary.

Peak Discharge from Ungaged Watersheds Using Synthetic Unit Hydrographs

A Soil Conservation Service engineer, Victor Mockus, developed a synthetic unit hydrograph method (reported in the SCS National Engineering Handbook, 1964). By Mockus' method a unit hydrograph is generated as the integral of an "instantaneous unit hydrograph," the unit hydrograph which theoretically results from a rainfall excess occurring instantaneously on all parts of a watershed. Either a curvilinear or a triangular

instantaneous unit hydrograph may be used. Except for generation of the synthetic unit hydrograph, the peak discharge is determined in the same manner as in the preceding methods.

Project Formulation Program-Hydrology

A private consulting firm (C.E.I.R., Inc.) has prepared a digital computer program for the Soil Conservation Service which permits solution of the runoff prediction equations described above. The program is versatile in that it permits a watershed to be divided into any number of subareas, permits the user to supply a unit hydrograph from a gaged watershed or call for the generation of a synthetic unit hydrograph, and permits a flood to be routed through any number of reserviors and any combination of stream channels. A considerable amount of watershed data must be supplied to the computer before the program can be run for a particular drainage basin, but any number of storms, having a variety of antecedent moisture conditions, can be solved.

The Soil Conservation Service does not usually run the program with actual storm data. Ordinarily, hypothetical design storm data are used. In cases where actual data are used, first runs are considered trial runs, and if the computer output does not yield runoff volumes which agree favorable with recorded volumes, adjustments are made in curve numbers or other watershed characteristics. Additional runs and adjustments are made until the generated runoff volume satisfactorily matches the recorded volume. This technique produces an "adjusted" watershed, for which hypothetical storms can then be run as desired, and runoff hydrographs generated.

TEST OF THE PROJECT FORMULATION PROGRAM - HYDROLOGY WITH DATA FROM ONE STORM AT DUCK CREEK

A rainstorm on Duck Creek watershed on June 13-16, 1965 produced a peak discharge at East Fork of 205 cfs, and at the main stream of Duck Creek of 342 cfs. The rain fell in three principal bursts, each about 24 hours apart, with total amounts varying from 2.26 to 4.30 inches in six precipitation stations on the watershed. Average total precipitation using Thiessen polygon weighting was 3.72 inches. Total surface runoff from the storm was 0.35 inches. The low yield is probably a result of dry antecedent soil conditions and the sporadic nature of the storm. There had been localized showers earlier in the month, but not general rain on the watershed during the three-week period perceding the June 16 event.

The storm was admittedly complex, and therefore difficult to model. After the analysis was under way an error in gage heights at the Duck Creek gaging station was discovered, which meant that the initially reported actual peak discharge and total runoff volume were sufficiently greater than the true values listed above.

In order to provide accurate watershed data as input to the program, level lines were run in the field the full length of each major stream channel, with meander lengths and directions, numerous stream cross sections and measurements of all stock ponds being obtained as well.

The first computer run generated a runoff event having a total yield of 0.57 inches. All the curve numbers used were then adjusted downward, and a new computer run made, this time yielding a total runoff volume of 0.43 inches.

The two runs produced hydrographs having peak discharges of 1144 and 1006 cfs respectively.

DISCUSSION OF RESULTS

The single storm on one watershed studied by SCS methods does not permit the drawing of any conclusions regarding the adequacy of the methods for determination of peak discharges. SCS hydrologists would require that the program be re-run using lower curve numbers to force the resulting runoff volume to match that actually produced, before hypothetical storms were used to produce design hydrographs. It was not possible to make these additional runs, so it can only be speculated that, based on the reduction of peak discharge from the first to second run, peak discharge from the "asjusted" watershed would be reduced to 820 cfs. This is still more than twice as high as the recorded peak flow of 342 cfs.

The Soil Conservation Service emphasizes that their methods are not intended to be used to reproduce actual runoff events that have occurred (although the formulas and techniques used were developed from actual storm and runoff data, of course). The intention is to produce, for a design storm, the best estimate of peak flow for spillway design.

Interim Report #5 (Ferris and Williams, 1968) describing the analysis of the SCS method was reviewed by D. C. Woo and F. K. Stovecik, for the Structures and Applied Mechanics Division, Federal Highway Administration. Woo and Stovecik had three comments: The SCS method is basically derived for application on agricultural (as opposed to rangeland) watersheds; an

article by Reich and Hiemstra (1967) was not cited in the report; data from the East Fork Duck Creek water level recorder for the June 16, 1965 storm should be used to extend the results.

The reviewers' first comment and the results of this investigation point to the need for extensive research to extend and improve the SCS technique for use on non-agricultural watersheds.

Reich and Hiemstra (1967) tested five methods for estimating peak flows, using 134 observed flood events on 45 streams. They pointed out that all five methods tested are intended to indicate flood behavior which is generally characteristic for typical conditions common in a particular region, rather than to "predict" any single event. They found that the SCS method underpredicted the observed event 88 percent of the time. (In contrast to the event studied in this investigation, for which the method overpredicted by a considerable amount). Kent (1967), discussing Reich and Hiemstra's paper, suggested that those authors had used an inappropriate technique to compute the estimated peak by the SCS method. With estimates modified by Kent, the SCS method underpredicted 52 percent of the time.

The East Fork Duck Creek water level records for the June 16, 1965 storm were used to make estimates of stream channel roughness, basin lag time, etc. A separate computer run for the East Fork alone could have been made by considering the east fork drainage as a separate watershed; or the East Fork hydrograph could have been used as input to the main watershed computer run for the purpose of studying the West Fork watershed separately. Limitations on use of the SCS computer precluded either of these options being tried.

CONCLUSIONS

The large amount of field data that must be obtained makes it appear that the SCS methods are not suitable at present for highway culvert design except in special situations which warrant the expense involved in the study.

None of the SCS methods assign return frequencies to the discharges obtained. Frequency is considered only through the frequency of the design storm used, and this may be entirely different than the frequency of the peak flow generated.

Results of this study verify conclusions which have been reached by others to the effect that the SCS methods cannot be used reliably to reproduce a hydrograph from a particular storm. The methods are intended to indicate characteristic flood behavior under typical conditions in the region.

SUMMARY

This chapter has reviewed methods used by the Soil Conservation Service for determination of peak flows, and has described a test of the principal methods using data from a single rain storm which occurred on Duck Creek watershed.

CHAPTER VII

MISCELLANEOUS PEAK DISCHARGE METHODS

Various public and private organizations have developed peak discharge relationships for design purposes. These are usually empirical formulas showing peak discharge as a function of area, geographical factors and sometimes watershed characteristics. Frequency appears in some of these relationships as a multiplying factor, and does not appear at all in others. This chapter describes some of these methods, and shows a comparison of results obtained by using several methods with actual recorded peak discharge on Project watersheds. Some of the methods were described in more detail by Dodge (1969).

SCS "COOK" METHOD

The Soil Conservation Service published a method in 1940 for estimating the hydrograph peak flow Q from the equation

$$Q = P \times R \times F \qquad (13)$$

for a watershed of not more that 2500 acres in size. In equation 13 P is determined from the chart in Figure 38. It is a function of drainage area, and certain watershed characteristics which are described in Table V. The rainfall factor R is really a geographical factor, and is simply determined from the map in Figure 38. F is a frequency factor, taken to be 1.00 for a 50 year frequency, 0.83 for a 24-year frequency, and 0.71 for a 10-year frequency. The rainfall factor R has not been defined for Montana.

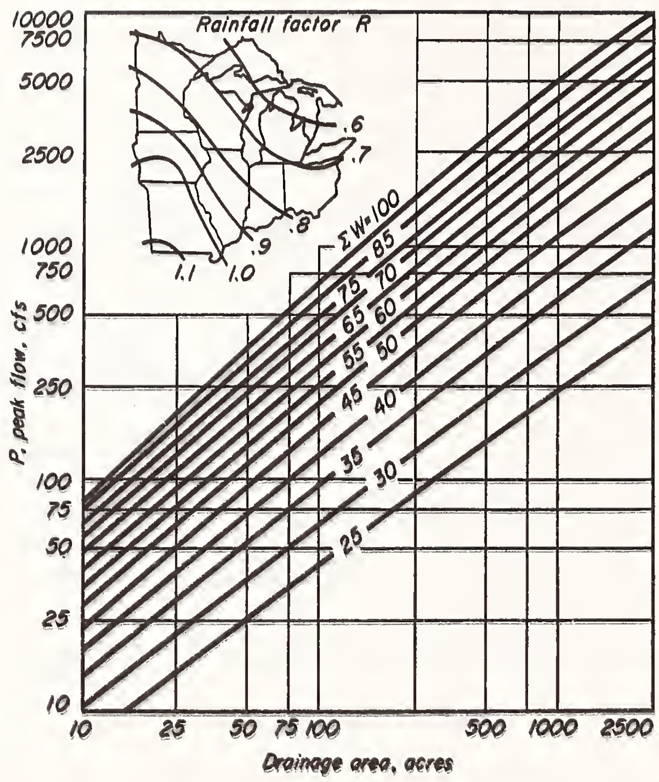


FIGURE 38 -- Chart and Map for Peak Flow Determination by the Cook Method.

Runoff Producing Characteristics of Drainage Basins with Corresponding Weights W
(The weights are shown in brackets)

Designation of Basin Characteristics	Runoff Producing Characteristics (100) Extreme	(75) High	(50) Normal	(25) Low
Relief	(40) Steep, rugged, terrain, with average slopes generally above 30 per cent	(30) Hilly, with average slopes of 10 to 30 per cent	(20) Rolling with average slopes of 5 to 10 per cent	(10) Relatively flat land, with average slopes of 0 to 5 per cent
Soil Infiltration	(20) No effective soil cover; either rock or thin soil mantle of negligible infiltration capacity.	(15) Slow to take up water; clay or other soil of low infiltration capacity, such as heavy gumbo.	(10) Normal, deep loam with infiltration about equal to that of typical prairie soil.	(5) High; deep sand or other soil that takes up water readily and rapidly.
Vegetal Cover	(20) No effective plant cover; bare except for very sparse cover.	(15) Poor to fair; clean-cultivated crops or poor natural cover; less than 10 per cent of drainage area under good cover.	(10) Fair to good; about 50 per cent of drainage area in good grassland, woodland, or equivalent cover; not more than 50 per cent of area in clean-cultivated crops.	(5) Good to excellent, about 90 per cent of drainage area in good grassland, woodland, or equivalent cover.
Surface Storage	(20) Negligible; surface depressions are few and shallow; drainage-ways steep and small; no ponds or marshes.	(15) Low; well-defined system of small drainage-ways; no ponds or marshes.	(10) Normal; considerable surface-depression storage; drainage system similar to that of typical prairie lands; lakes, ponds and marshes less than 2 per cent of drainage area.	(5) High; surface-depression storage high; drainage system not sharply defined; large flood-plain storage or a large number of lakes, ponds or marshes.

TABLE V. Runoff Producing Characteristics of Drainage Basins with Corresponding Weights W (The weights are shown in brackets).

BUREAU OF PUBLIC ROADS METHOD

The Bureau of Public Roads in 1951 developed a method similar to the Cook method wherein the design peak discharge is computed from the formula

$$Q_{design} = RF \times LF \times LF\ FF \times Q \qquad (14)$$

Q is obtained as a function of area for basins up to 1000 acres in size from Figure 39. A table supplies values of LF, a land-use and slope factor; the map in Figure 40 supplies RF, a geographical, or rainfall factor. As with the Cook method a frequency factor FF adjusts the equation to the desired frequency. Published values of RF cover only areas of the United States east of Montana.

USBPR "POTTER" METHOD

A method for determining peak flows and associated recurrence intervals was devised for the U.S. Bureau of Public Roads by William D. Potter (1961). This method was the result of a research study which as limited to watersheds with areas less than 25 square miles located east of the 105th meridian. The study was made on a sample of 243 ungaged watersheds and 96 gaged watersheds.

The method groups all watersheds into four physiographic zones, based on data supplied by the Soil Conservation Service. These zones define large regions which are underlain by similar rock formations. The area of Montana east of the 106th meridian is mostly located in Zone II, with a small section located in Zone I. Figure 41 shows a zone classification map for the North Central States.

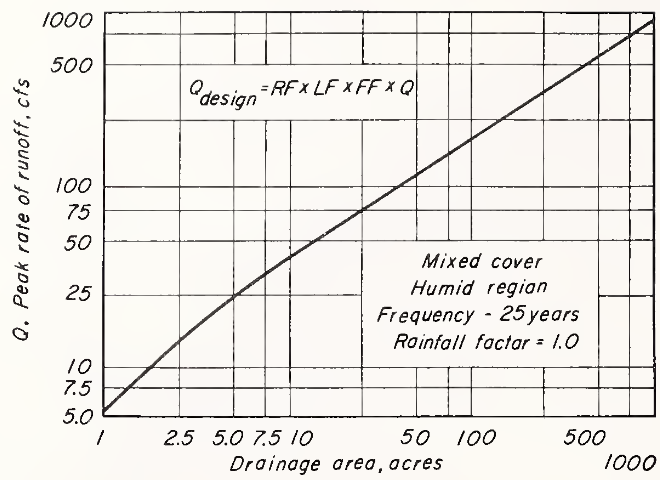


FIGURE 39 -- Peak Rates of Runoff for Drainage Basins Under 1,000 Acres (from Bureau of Public Roads Manual, August 1951)

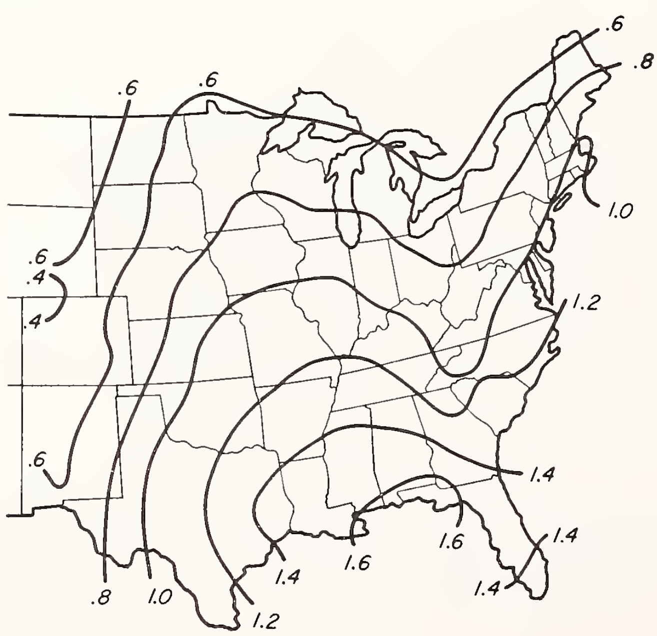


FIGURE 40 -- Rainfall Factors. Use with Figure 39 in Estimating Peak Rates of Runoff (from Bureau of Public Roads Manual, July, 1951)

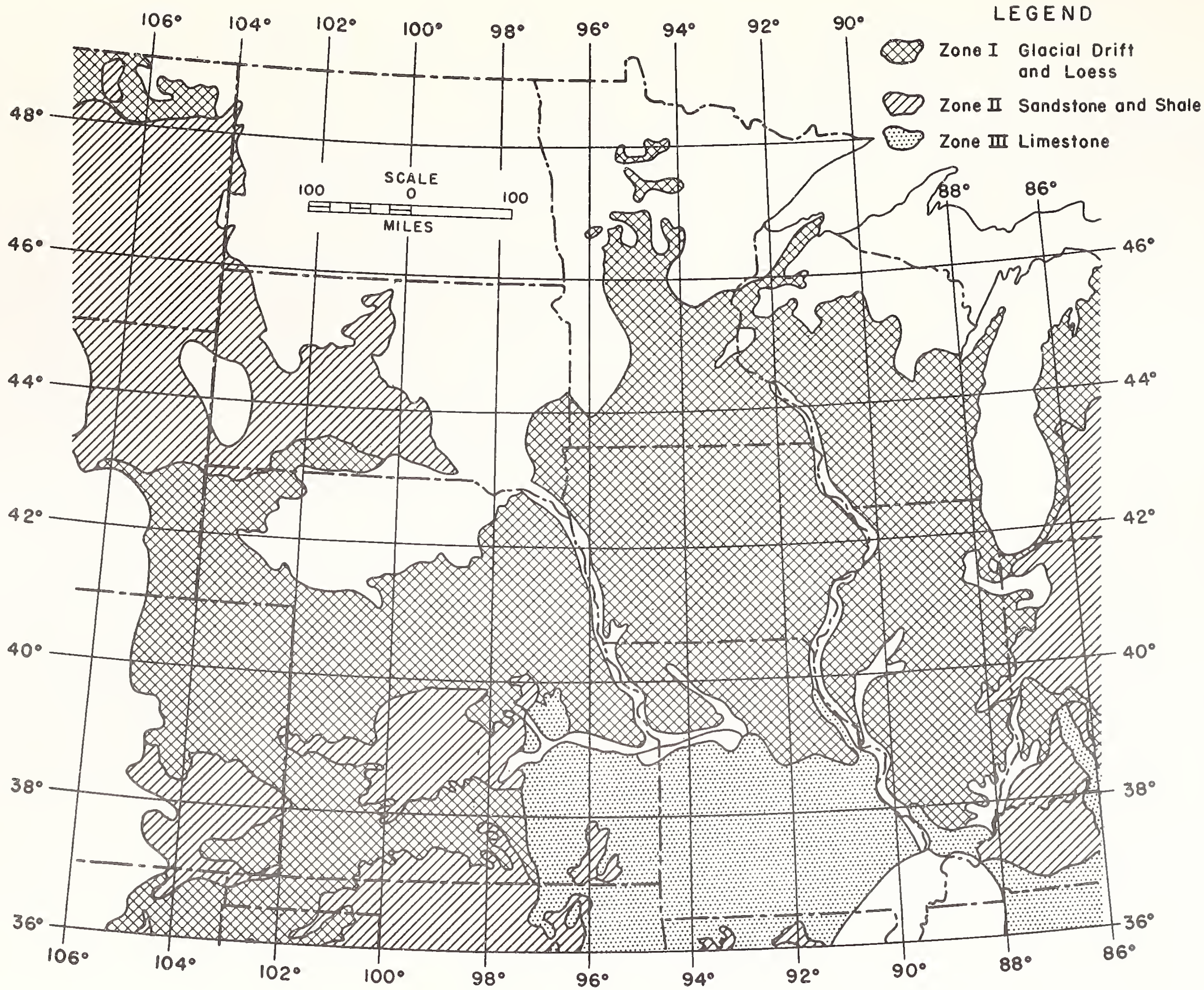


FIGURE 41 -- Potter Method - Classification by Zones: North Central States

A topographic index T is determined from

$$T = \frac{.3L}{\sqrt{S_1}} + \frac{.7L}{\sqrt{S_2}} \qquad (15)$$

where L = total length of stream channel

S_1 and S_2 are the slopes of the upper 0.3 and lower 0.7 of the stream channel respectively.

A precipitation index P is determined to be the amount of rain which may be expected to be equalled or exceeded on an average once in ten years for a 60 minute duration.

A trial value for the peak flow with a 10-year recurrence interval, $\hat{Q}_{10(ATP)}$ is obtained graphically. Figures 42 and 43 are for Zones I and II respectively. Potter developed such graphs for each of the four zones.

Figure 44 (for Zones I and II or a similar chart for zones III and IV) is used to determine an estimated value for the topographic index, $\hat{T}_{AP}$. The percent difference between estimated and measured values of topographic index is obtained from

$$D = \left[\frac{\hat{T}_{AP} - T}{\hat{T}_{AP}} \right] X\ 100$$

If D is less than 30 percent it is assumed that the trial value of $\hat{Q}_{10\ (ATP)}$ is satisfactory, and this value is accepted as the peak discharge with 10-year recurrence interval. If D is equal to or greater than 30 percent,

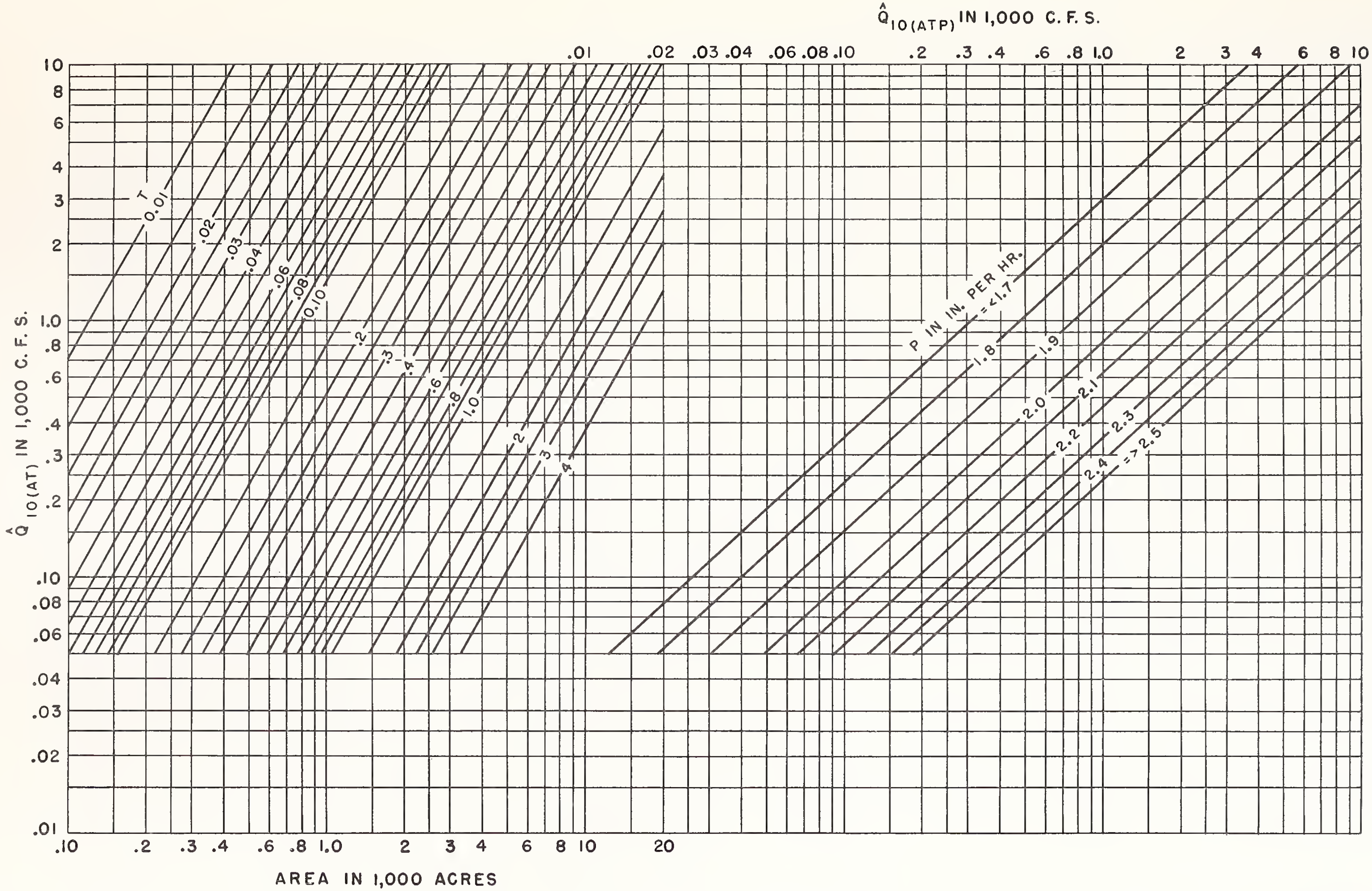


FIGURE 42 -- Potter Method - Relations between Q_{10}, A, T, and P: Zone I.

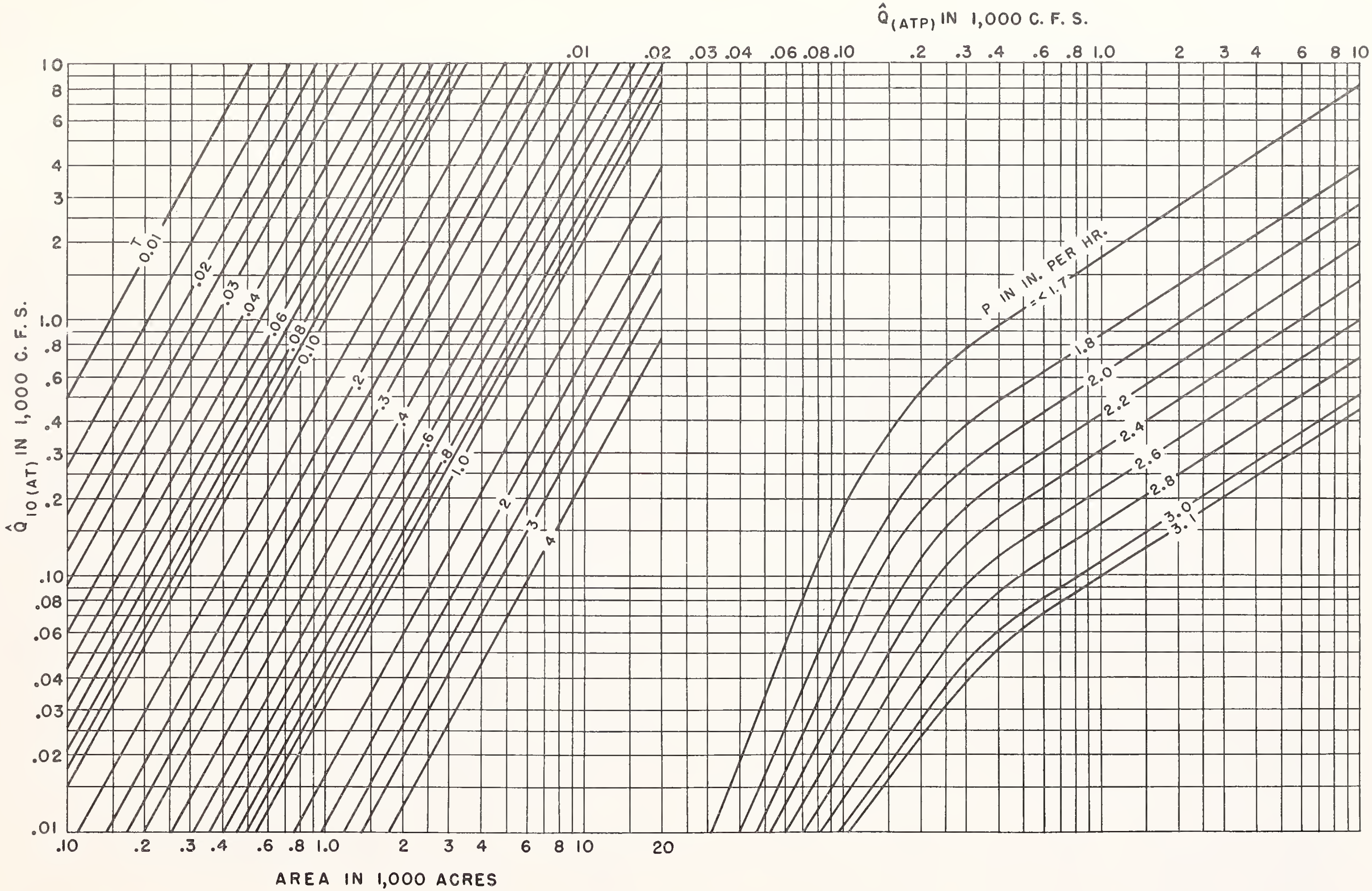


FIGURE 43 -- Potter Method - Relations between Q_{10}, A, T, and P: Zone II.

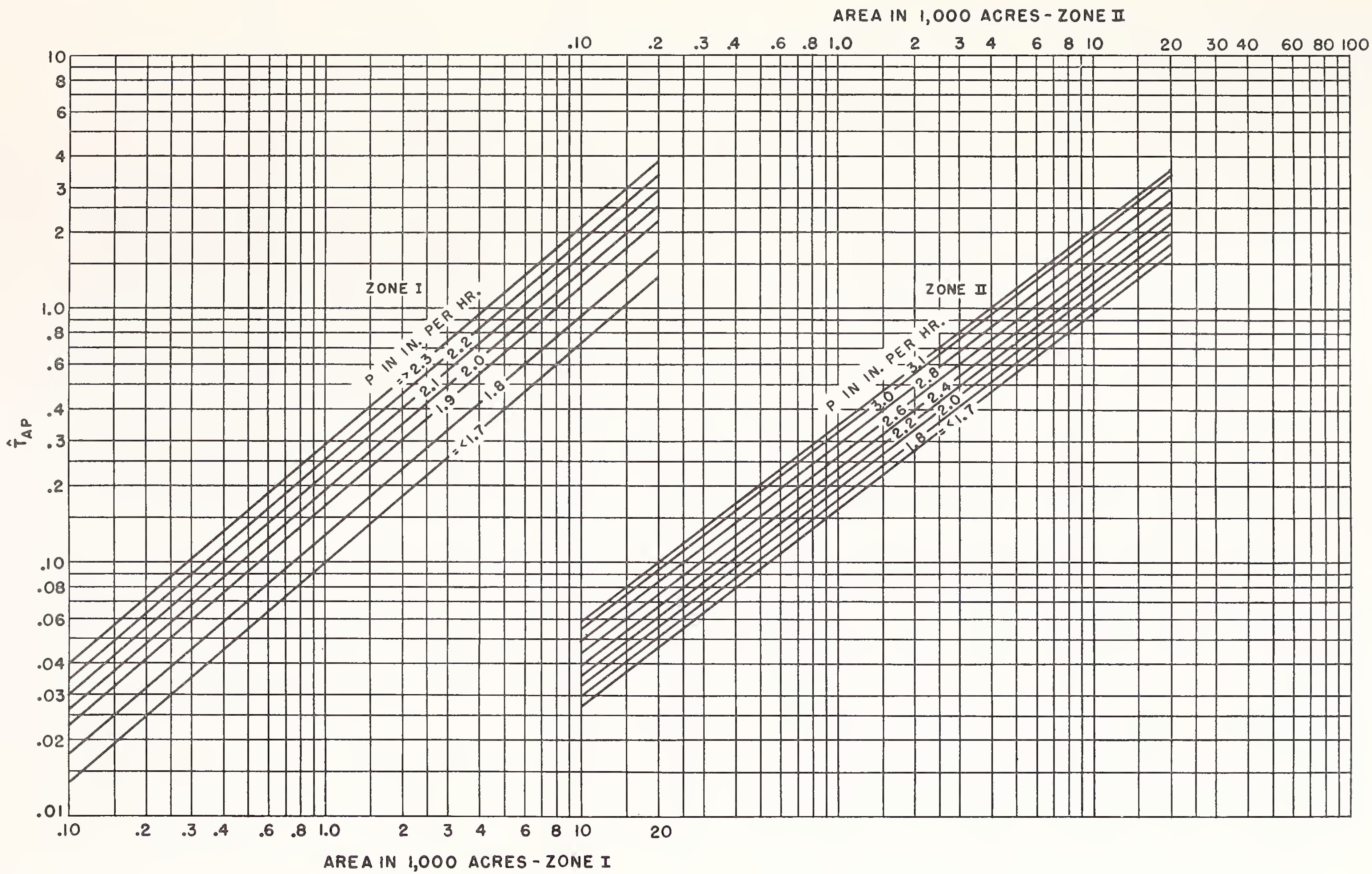


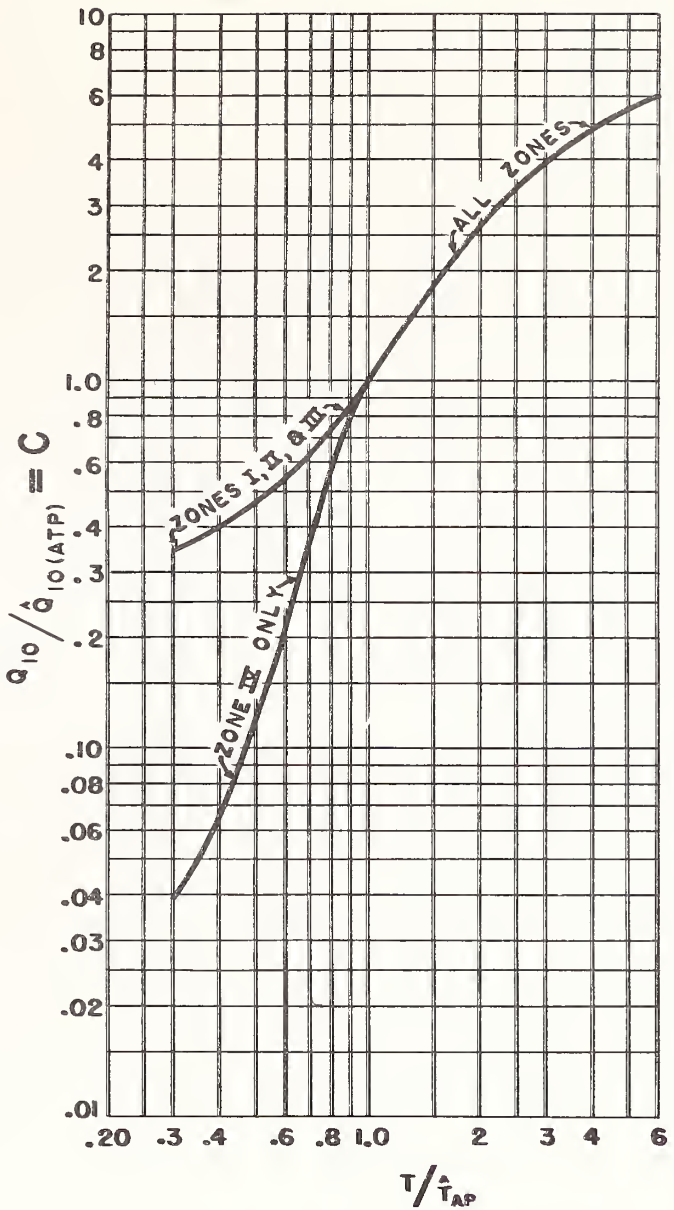
FIGURE 44 -- Potter Method - Relations between T, A, and P: Zones I and II.

the ratio $T/\hat{T}_{AP}$ is computed, and this value is used in Figure 45A to obtain a multiplier, C. The trial value of $\hat{Q}_{10\ (ATP)}$ is multiplied by C to obtain the 10-year discharge. Potter suggested that peak discharges for other recurrence intervals could be obtained by plotting Q_{10} and Q_{50} on extremal probability paper and drawing a straight line through the plotted points.

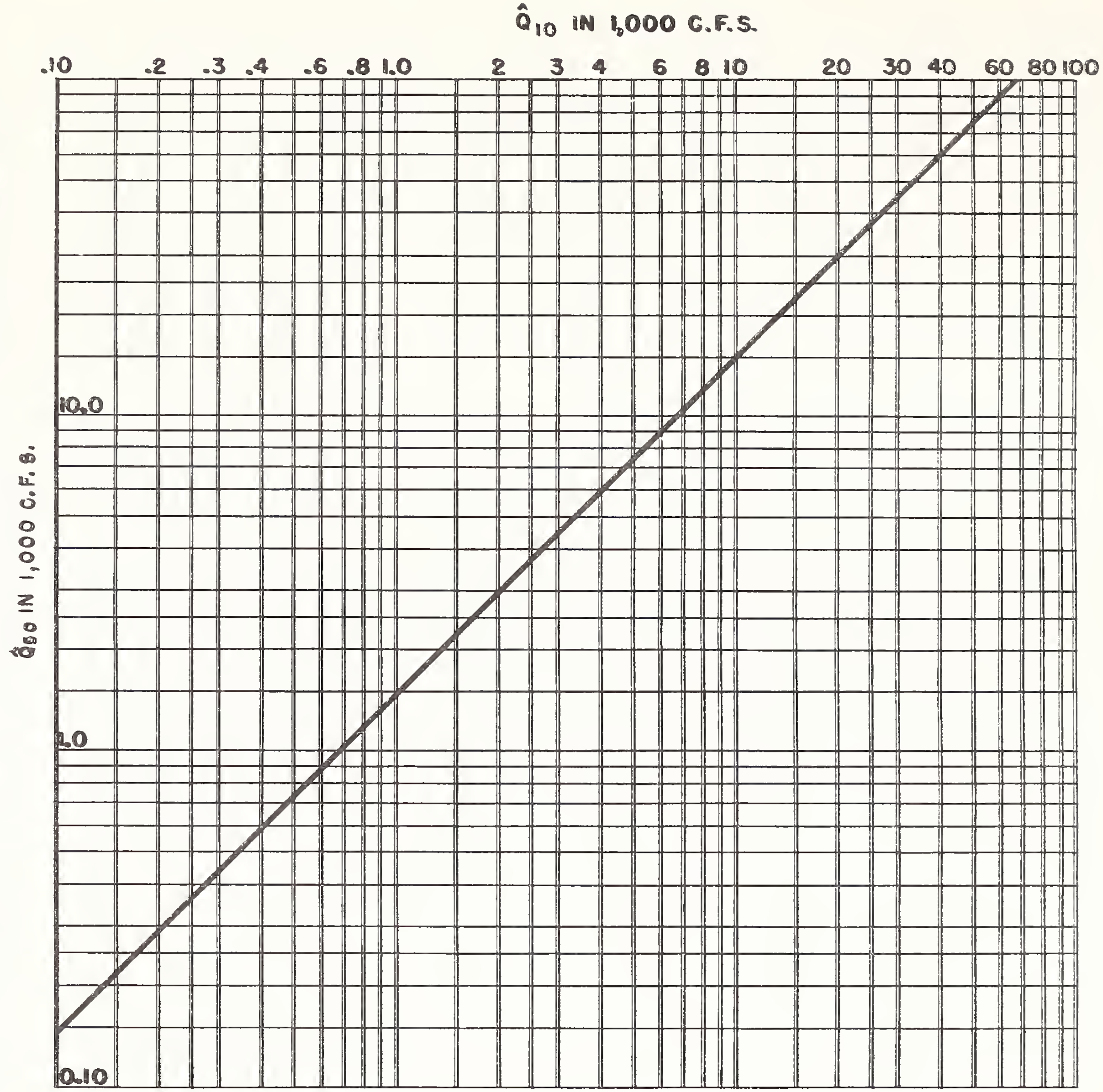
Except for the extreme eastern part of Montana, the Potter method is not applicable in this state. For purposes of comparison however, it was assumed that eastern Montana watersheds could be classed in Zone II. Figure 46 shows the calculations used in applying the method to Bacon Creek watershed.

NORTHERN PACIFIC RAILWAY METHOD

For many years the Northern Pacific Railway used the Myers formula, wherein the square feet of opening required is equal to a coefficient times the square root of the drainage area. Assistant Chief Engineer, Walter Bjorklund stated in a letter in 1963 that they had used coefficients as low as 0.5 and as high as 6.0. In recent years, design has been based upon records of high runoff which have been recorded in the same general area. The NP has had several culverts which have operated under a head, and for which peak discharge has been computed. Usually these were of sufficient frequency that they have been able to determine what to expect in a particular area. By superimposing a similar storm on other drainage areas, Mr. Bjorklund indicates it is possible to obtain the probable design runoff.



a) -- Coefficient C as a function of T/T_{AP}



b) -- Relation between Q_{10} and Q_{50} for all Zones.

FIGURE 45 -- Potter Method.

STEP A Identification of watershed BACON CREEK

Location: Topographic map quadrangle ______ Principal stream MUSSELSHELL

A-1 Location of crossing: Latitude $46^{\circ}12'$ Longitude $109^{\circ}50'$

A-2 Area of watershed, A (planimetered) = 13.55 1,000 acres.

A-3 Principal stream length: L = 10.8 miles; 0.3L = 3.24 miles; 0.7L = 7.56 miles.

Elevations on principal stream:

a, at headwater 4965 ft.; b, at 0.7L above crossing 4670 ft.; c, at crossing 4200 ft.

S_1 = (el. a - el. b) ÷ 0.3L = (4965 - 4670) ÷ 3.24 = 195 ÷ 3.24 = 60.19 ft./mi.; $\sqrt{S_1}$ = 7.76

S_2 = (el. b - el. c) ÷ 0.7L = (4670 - 4200) ÷ 7.56 = 470 ÷ 7.56 = 62.17 ft./mi.; $\sqrt{S_2}$ = 7.89

T = (0.3L ÷ $\sqrt{S_1}$) + (0.7L ÷ $\sqrt{S_2}$) = (3.24 ÷ 7.76) + (7.56 ÷ 7.89) = .418 + .957 = 1.375

STEP B From step A-1: Lat. ______ Long. ______

B-1 From figure B-1a, b, c, or d: Zone II B-2 From figure B-2a, b, c, or d: P = 1.0 in.

STEP C From steps A & B: Zone II A = 13.55 P = 1.0 T = 1.375

From figure C-1a, b, c, or d: $\hat{Q}_{10(ATP)}$ = 1.2 1,000 c.f.s.

STEP D From steps A & B: Zone II A = 13.55 P = 1.0 T = 1.375

From figure D-1a or b: $\hat{T}_{AP}$ = 1.200

Error = ($\hat{T}_{AP}$ - T) ÷ $\hat{T}_{AP}$ x 100 = (1.200 - 1.375) ÷ 1.20 x 100 = .175 ÷ 1.20 = 14.6%

STEP E From step D: Error = 14.6 %.

E-1 & 2 Use only if error is equal to or greater than 30%.

From steps A, B, C, & D: Zone ______ T = ______ $\hat{T}_{AP}$ = ______ $\hat{Q}_{10(ATP)}$ = ______

T ÷ $\hat{T}_{AP}$ = ______ ÷ ______ = ______ From figure E-1: Coefficient C = ______

$\hat{Q}_{10(C)} = \hat{Q}_{10(ATP)}$ x C = ______ x ______ = ______ 1,000 c.f.s.

E-3 From steps C, D, & E-2: $\hat{Q}_{10(ATP)}$ = ______ $\hat{Q}_{10(C)}$ = ______ Error = ______ %

When error is less than 30% .... $\hat{Q}_{10} = \hat{Q}_{10(ATP)}$ = 1200 cfs

When error is equal to or greater than 30%, $\hat{Q}_{10} = \hat{Q}_{10(C)}$ = ______

From figure E-3, $\hat{Q}_{50}$ = 1800 cfs

STEP F From step E-3: $\hat{Q}_{10}$ = 1200 $\hat{Q}_{50}$ = 1800 cfs

Plot $\hat{Q}_{10}$ and $\hat{Q}_{50}$ on extremal probability paper; connect points;

read from extended curve: $\hat{Q}_{25}$ = 1530 $\hat{Q}_{100}$ = 2060 $\hat{Q}_{200}$ = 2300 $\hat{Q}_{500}$ = 2680

FIGURE 46. Potter Method: Suggested Work Sheet for Estimating Peak Rate of Runoff of Small Watersheds.

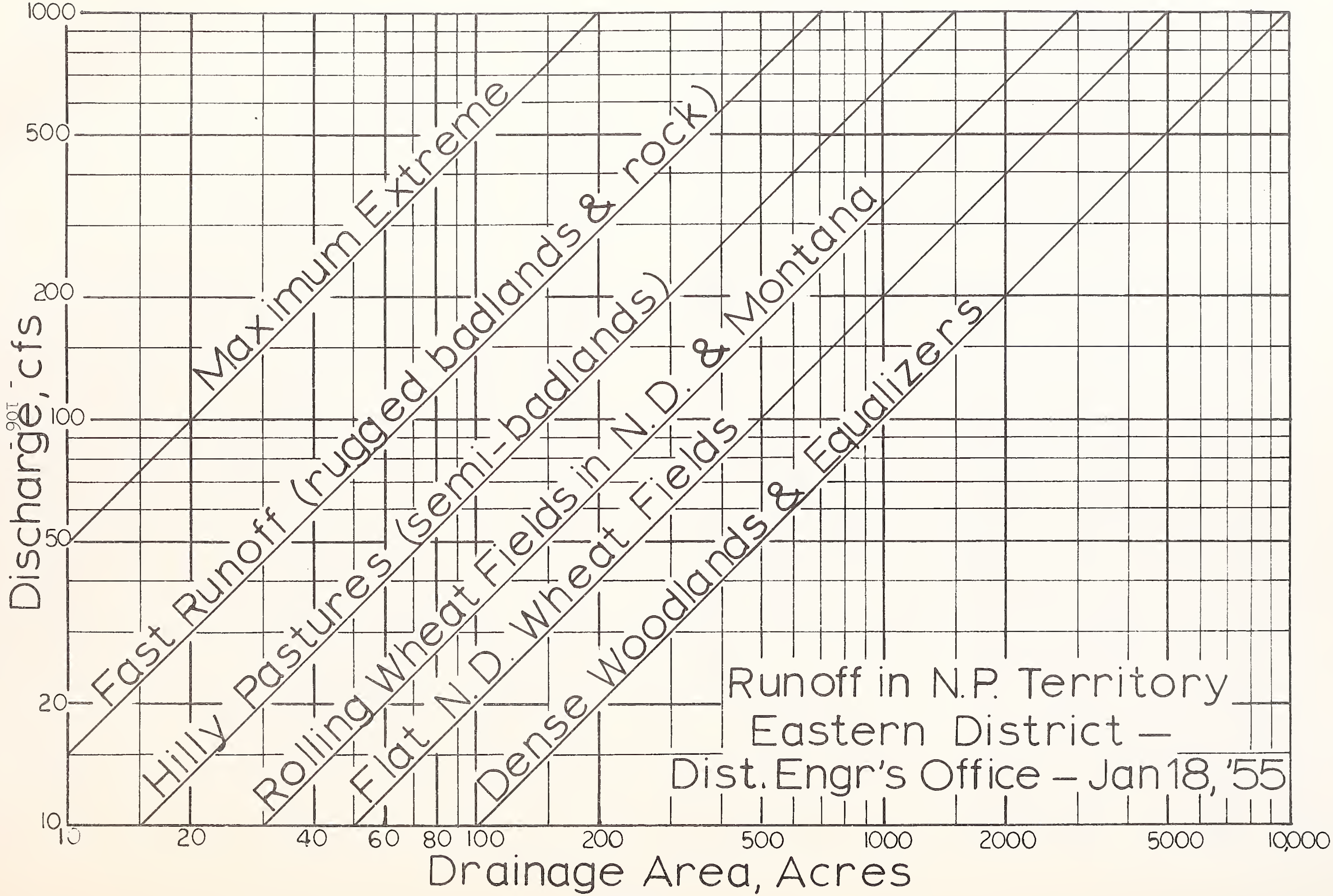
Mr. Bjorklund has prepared a chart (Figure 47) on the basis of runoffs which have actually been experienced on the NP.

The line designated "Rolling Wheat Fields in North Dakota and Montana and Rolling Pasture in Minnesota and Wisconsin" was indicated by Mr. Bjorklund as applying to much of their Yellowstone Division (from Mandan, North Dakota to Livingston, Montana) except not in Badlands areas.

The line designated "Hilly Pastures (Semi Badlands)" applies to most of the NP lines in eastern Montana (Glendive-Sidney, Glendive-Brockway, Glendive-Forsyth, Forsyth-Colstrip). Exceptions are the bluff area east of Miles City, the bluff area east and west of Rosebud, and the bluff area between Myers and Big Horn. In these latter areas the line designated "Fast Runoff (Rugged Badlands and Rock)" applies.

The line designated "Maximum Extrene" indicates some extremely high runoffs which have been encountered on lines other than the NP. Included are some floods in Missouri, Kansas and Nebraska.

The NP method described is intended for areas less that 10,000 acres in size and discharges not over 1,000 cfs. Mr. Bjorklund indicated, however, that they would be reluctant to design a culvert for a drainage area larger that 3,000 acreas or for a discharge of more than 1500 cfs.



Runoff in N.P. Territory
Eastern District —
Dist. Engr's Office — Jan 18, '55
Maximum Extreme
Fast Runoff (rugged badlands & rock)
Hilly Pastures (semi-badlands)
Rolling Wheat Fields in N.D. & Montana
Flat N.D. Wheat Fields
Dense Woodlands & Equalizers
Discharge, cfs
1000
500
200
100
50
20
10
Drainage Area, Acres
10
20
40
60
80
100
200
500
1000
2000
5000
10,000

FIGURE 47

U.S. GEOLOGICAL SURVEY METHODS IN MONTANA

Since inauguration of the small-area peak-flow highway program in Montana in 1955 the U.S. Geological Survey has released three reports, each presenting methods for obtaining peak discharge rates having return frequencies of 20 or 25 years.

Berwick (1958) proposed a method for determining magnitude and frequency of floods, applicable to any drainage area from 35 to 3,000 square miles, in most of eastern Montana. A composite frequency curve expressing the ratio of the mean annual flood to floods having return period of up to 20 years was developed using data from 16 stations. A regression was derived, relating mean annual flood to drainage area and mean elevation of the basin.

An interim report in 1963 by Boner revised Berwick's report, and expanded the relationship to cover drainage areas ranging from less than 1 square mile to 3,200 square miles. Boner's technique was the same as that of Berwick, developing a composite frequency curve expressing ratio of mean annual flood to floods having return period of up to 25 years using data from 19 crest stage gages and 21 long-term stations. A regression equation was derived, relating mean annual flood to drainage area, mean basin elevation, meander length of main stream course, and a geographical factor. The method is applicable only to areas of Montana east of Havre, Lewistown and Columbus, and to basins under 6000 feet in elevation.

Berwick and Boner each based their procedures on a method originally proposed in 1960 by Dalrymple. Patterson in 1966 applied this technique to most of the Missouri River basin above Sioux City, and Bodhaine and Thomas did the same in 1964 for streams in Montana lying in the upper Columbia River basin. Both of these latter studies provide magnitude and frequency of expected floods for return periods up to 50 years and for drainage basins larger than 100 square miles.

Boner and Omang, in 1967, used the 10-year flood as the index flood, together with ratio of 25 year flood to 10-year flood, to determine the flood with 25-year return frequency. Montana was divided into 13 geographical areas. The 10-year flood is a function of which geographical area the watershed is in, the area of the watershed and, in 5 of the 13 geographical areas, the average annual runoff. The ratio of 25-year flood to 10-year flood to 10-year flood is different for each of the 13 areas. Boner and Omang suggest that the reliability of their method is fair, and for predicting a 25-year flood it is poor.

COMPARISON OF VARIOUS METHODS

Table VI shows 25-year peak discharges obtained for the Project watersheds, using the Boner, Boner-Omang, Gumbel and "Potter" methods. Design discharges for the two watersheds which are under 10,000 acres were also obtained using the Northern Pacific method, and these are also shown in Table VI. Maximum discharges which have actually been recorded on the watersheds are shown for comparison.

TABLE VI: Comparison of Peak Discharges Computed by Various Methods

(All flows in cubic feet per second)

Watershed	Area, Square Miles	Years of Record	Experienced Mean Annual Flood	Peak Discharge of Record	Boner Mean Annual Flood	Boner 25-Year Peak Flood	Boner-Omang 10-Year Peak Flood	Boner-Omang 25-Year Peak Flood	N. P. Railway Design Discharge	"Potter" Method 25-Year Peak ###	"Gumbel" Method 25-Year Peak Flood
Bacon Creek	17.97	14	416	3230	127	457	600*	870*		1530	2700
Duck Creek	53.79	13	326	1000	453	1630	900	1305		4450	1240
E. Fork Duck	13.67	15	186	650	208	749	530	768	6500#	1080	660
Hump Creek	7.61	10	61.1	307	78	281	140**	168	1800##	810	326
Lone Man Coulee	14.10	10	280	1740***	119****	429	235	352		1360	1727

* Bacon Creek is on the line separating geographical areas G and L (Boner-Omang). These values computed assuming watershed is in area L. If it were in area G the 10-year peak by Boner-Omang method is 190 cfs and 25-year peak is 266 cfs.

** Hump Creek is in geographical area J (Boner-Omang). For this area Boner-Omang do not show a 10-year peak for basins under 10 square miles. This value was obtained by extrapolation.

*** A peak of 1820 cfs was measured in June 1948 from 11.4 square miles.

**** Lone Man Coulee lies outside the geographical area included in Boner's study. This value was obtained by using a geographical factor G = 2.02.

\# Extrapolated using line for "Hilly Pastures (Semi-Badlands)."

\## Extrapolated using line for "Rolling Wheat Fields in North Dakota and Montana."

\### The watersheds all lie outside the geographical area included in Potter's study. These values were obtained by assuming all watersheds lie in Zone II.

The Boner and the Boner-Omang methods give 25-year peak discharges which are similar to the maximum recorded discharges at Duck Creek and East Fork Duck Creek, but they give discharges which are smaller than those which have been experienced at Bacon Creek, Hump Creek and Lone Man Coulee. The Gumbel method gives discharges which are larger than any which have been experienced at Duck Creek, East Fork Duck Creek and Hump Creek; while at Bacon Creek and Lone Man Coulee the method predicts peak discharges somewhat smaller than those which have been experienced. The "Potter" method of course was not intended to be applied in Montana, and the values were included here for comparison only. The Northern Pacific method gives discharges which are much larger than any which have been experienced on the two watersheds where the method could be applied.

True return periods are not known from the recorded discharges on these streams, but it should be noted that residents of the Bacon Creek area report that comparable floods have occurred there about once every 30 years; and that since 1948 Lone Man Coulee has experienced three events which were larger than the 25-year peaks predicted by either Boner or Boner-Omang.

CONCLUSIONS

None of the methods discussed in this chapter, appears to be as reliable in predicting peak flows on the five Project watersheds as the Gumbel method which is a stochastic method.

CHAPTER VIII

COMPARISON OF STOCHASTIC PEAK FLOW METHODS

This chapter reports a test of the goodness of seven frequency distributions for prediction of peak discharges having specific return frequencies on the five project watersheds. (For this test East Duck Creek was considered as a separate watershed). The test follows the procedures advanced by Gupta (1968) in which he tested ten methods on six watersheds located at LaCrosse, Wisconsin.

PROCEDURE

Reference has been made elsewhere in this report to the multitude of methods which have been proposed for the prediction of the peak discharge which has some specified return frequency. The question which arises is: Is one of these methods more reliable than others for use in Montana? Clearly, there is no absolute answer to this question at the present time because the exact correct discharges and frequencies are not known. However, it is possible to use statistical methods to compare various methods with each other and with such recorded data as may be available.

Seven methods were selected for comparison, and the recorded data from the Project watersheds were used in the analysis. The methods used were the extreme value distribution (Gumbel's method). The Log-Pearson Type III method, four versions of Gringorten's distributions, and

the peak rainfall frequency-peak flow frequency method described in Chapter II of this report.

The actual annual maximum discharges which have been recorded on the five watersheds were ranked, and assumed return periods were computed from the widely accepted formula

$$t_r = \frac{N + 1}{m} \tag{17}$$

where t_r = return period

N = number of years of data

m = ranking order of the flood (largest of record = 1, next = 2, etc.)

These discharges and return periods were assumed for purposes of this analysis to be the absolute or correct values, so as to have a basis against which to compare the various prediction methods.

For each of the seven methods, and for each of the five watersheds, predicted discharges for the return frequencies established from the recorded data were determined. Each of the methods is described elsewhere in this report and will not be discussed again at this point except to note that special calculations were necessary with the peak rainfall frequency-peak flow frequency method. Values of R_i, D_i and F_i used in this method have been established only for i=50 years, and accurate prediction of peak discharges for other return periods is not possible. Estimates of R_i for the required return periods were made for the geographic areas involved, by using Gumbel's technique to establish rainfall intensities at the lower return periods. D_i and F_i were assumed not to change at the lower return

periods. Each of the methods is purely stochastic except for the peak rainfall frequency-peak flow frequency method.

Results of the study are tabulated in Appendix G, and are shown graphically in Figures 48 to 52. (The peak rainfall frequency-peak flow frequency method is identified on the graphs as the 'Robinson' method.)

For each of the seven methods the coefficient of determination, R^2, was then computed from

$$R^2 = 1 - \frac{\sum(\text{Predicted Event} -- \text{Observed Event})^2}{\sum(\text{Observed Event} -- \text{Mean of Observed Events})^2} \tag{18}$$

The Gumbel method and all four of the Gringorten methods predicted negative discharges at the lowest return frequencies. For these methods R^2 values were computed twice, first by using the negative predictions, and second by assigning a discharge of zero to each of the negative predictions. R^2 values are tabulated for the two techniques in Table VII. The largest values of R^2 represent the best correlation with the recorded data; also shown on Table VII are rankings, with the method that correlates best with recorded data on a watershed being ranked 1, the method that correlates next best being ranked 2, etc. Table VIII repeats Table VII, except that methods are shown as columns and watersheds as rows, and the rankings now indicate for which watershed each method correlated best. (For example, the Gumbel method correlated best with recorded data on Duck Creek, next best with East Fork of Duck Creek, etc.)

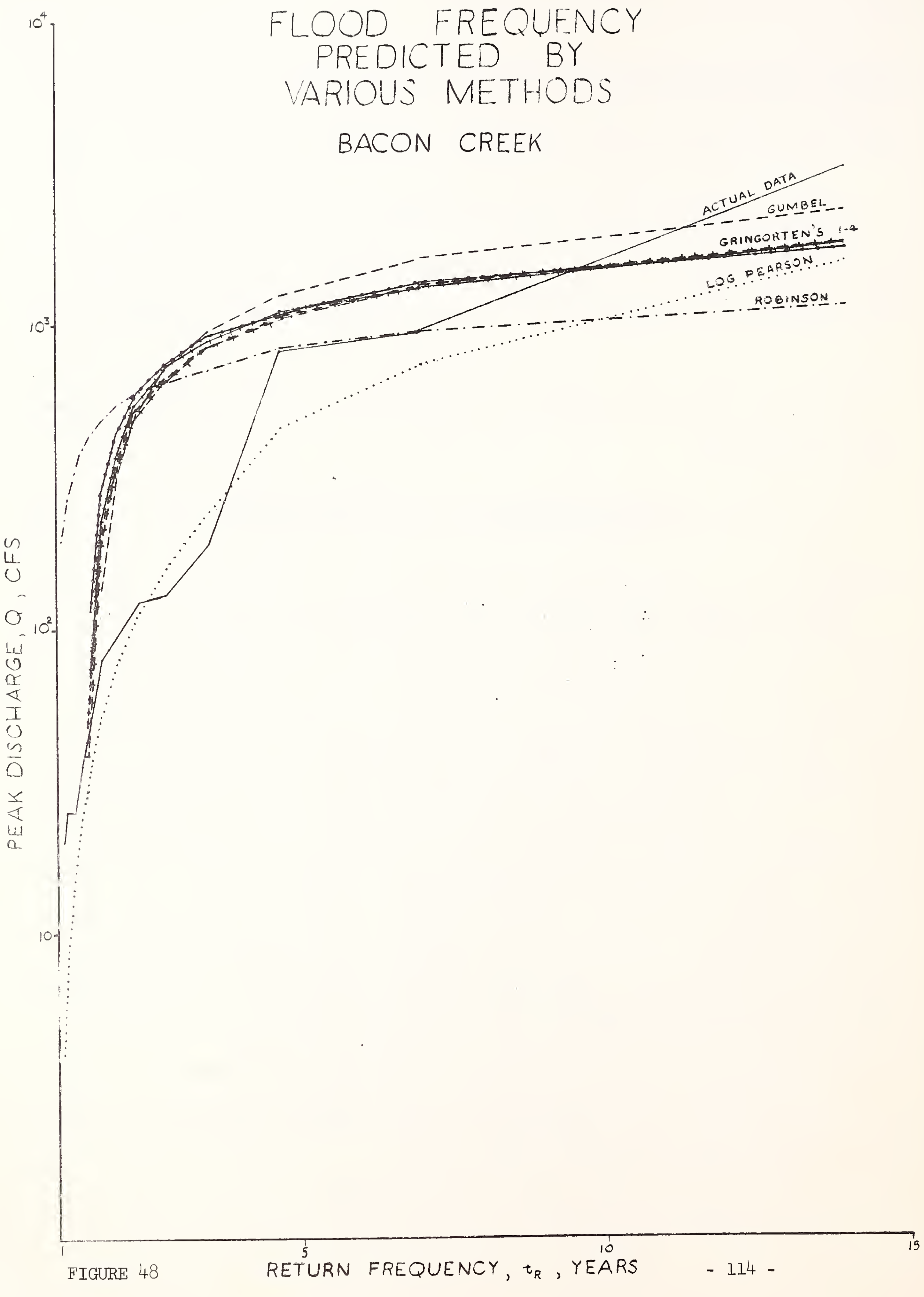

FLOOD FREQUENCY
PREDICTED BY
VARIOUS METHODS
BACON CREEK
ACTUAL DATA
GUMBEL
GRINGORTEN'S 1-4
LOG PEARSON
ROBINSON
PEAK DISCHARGE, Q, CFS
10^4
10^3
10^2
10
1
5
10
15
RETURN FREQUENCY, t_R, YEARS

FIGURE 48

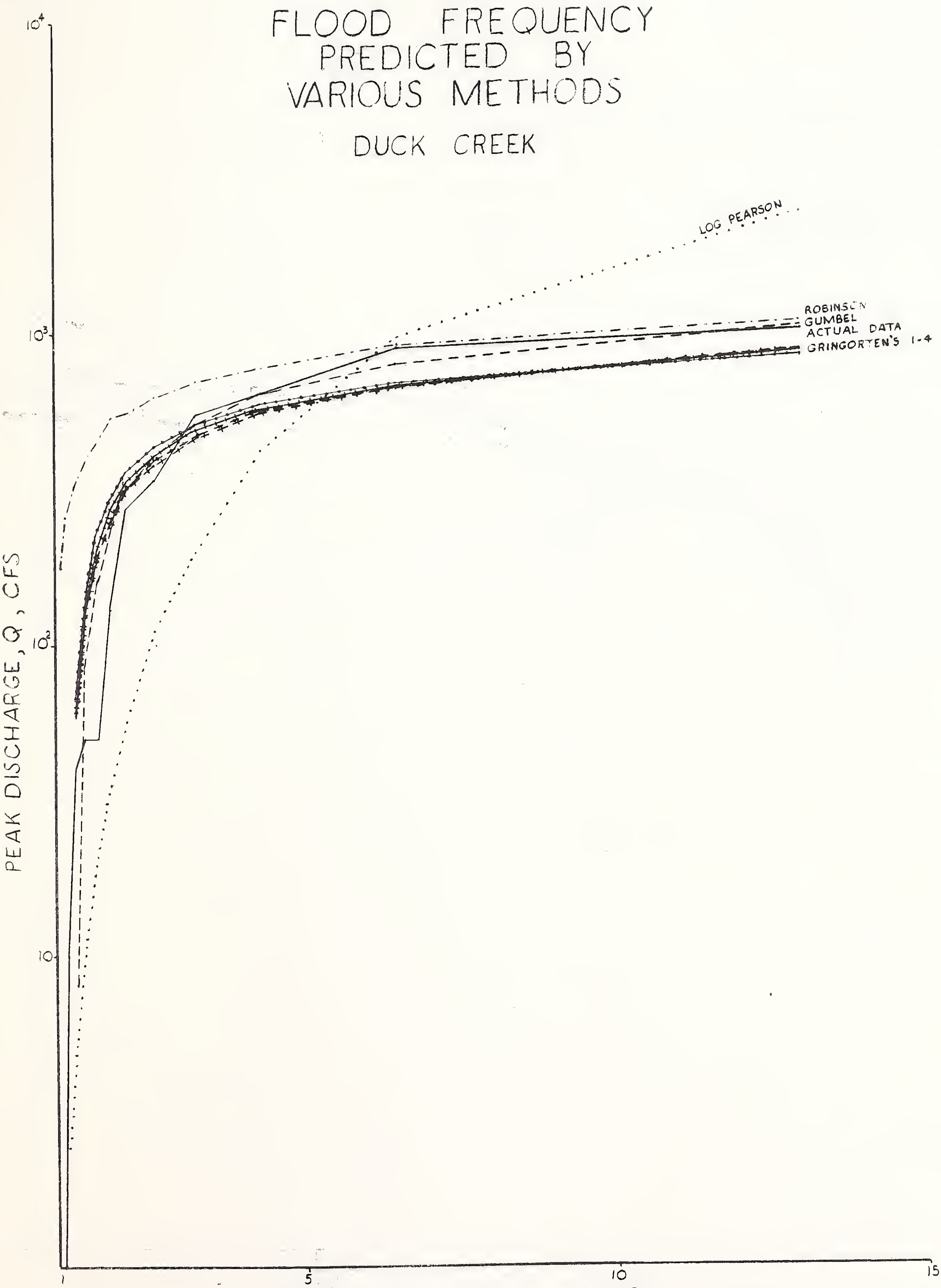

FLOOD FREQUENCY
PREDICTED BY
VARIOUS METHODS
DUCK CREEK
LOG PEARSON
ROBINSON
GUMBEL
ACTUAL DATA
GRINGORTEN'S 1-4
PEAK DISCHARGE, Q, CFS
RETURN FREQUENCY, t_R, YEARS
10^4
10^3
10^2
10
1
5
10
15

FIGURE 49

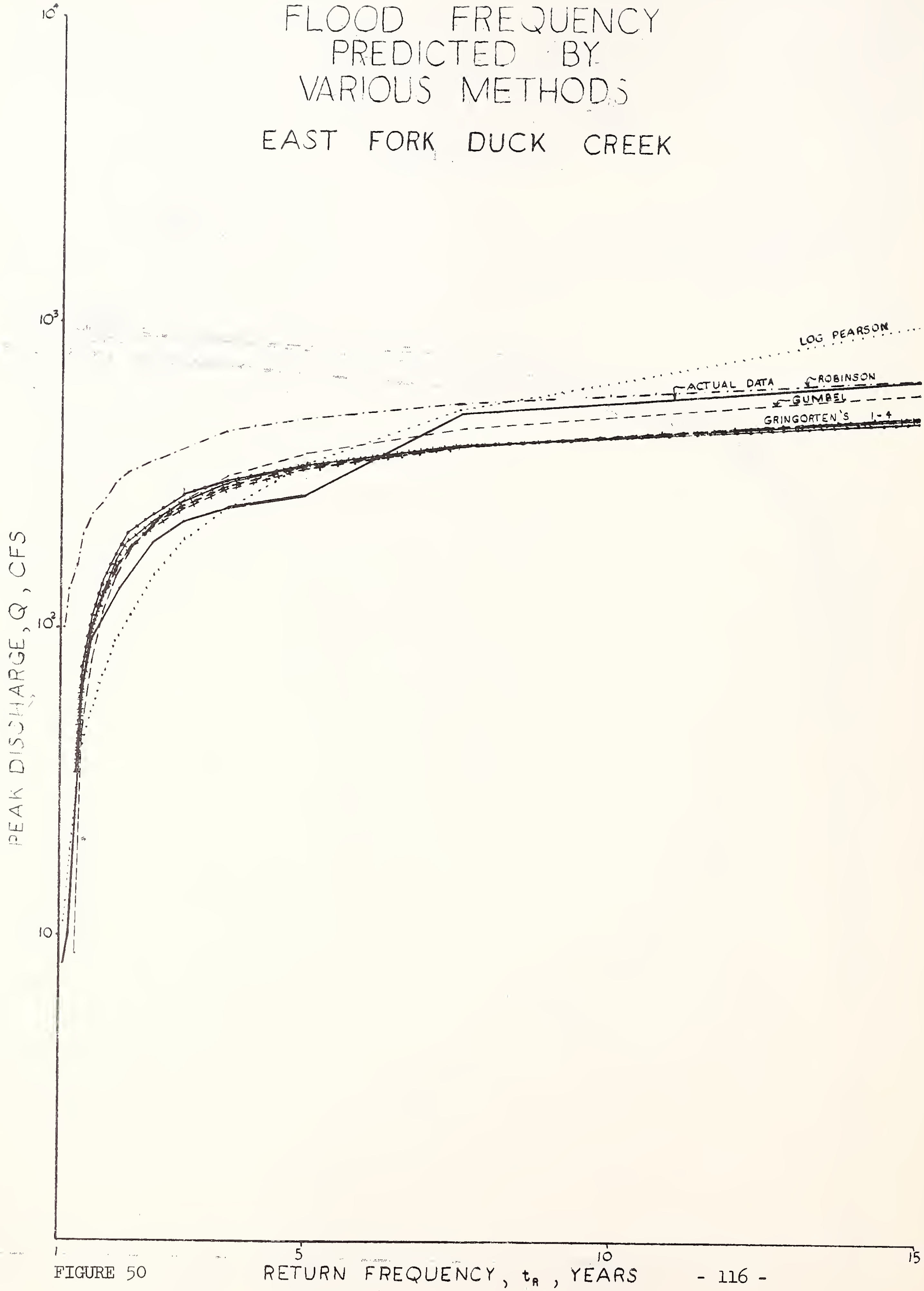
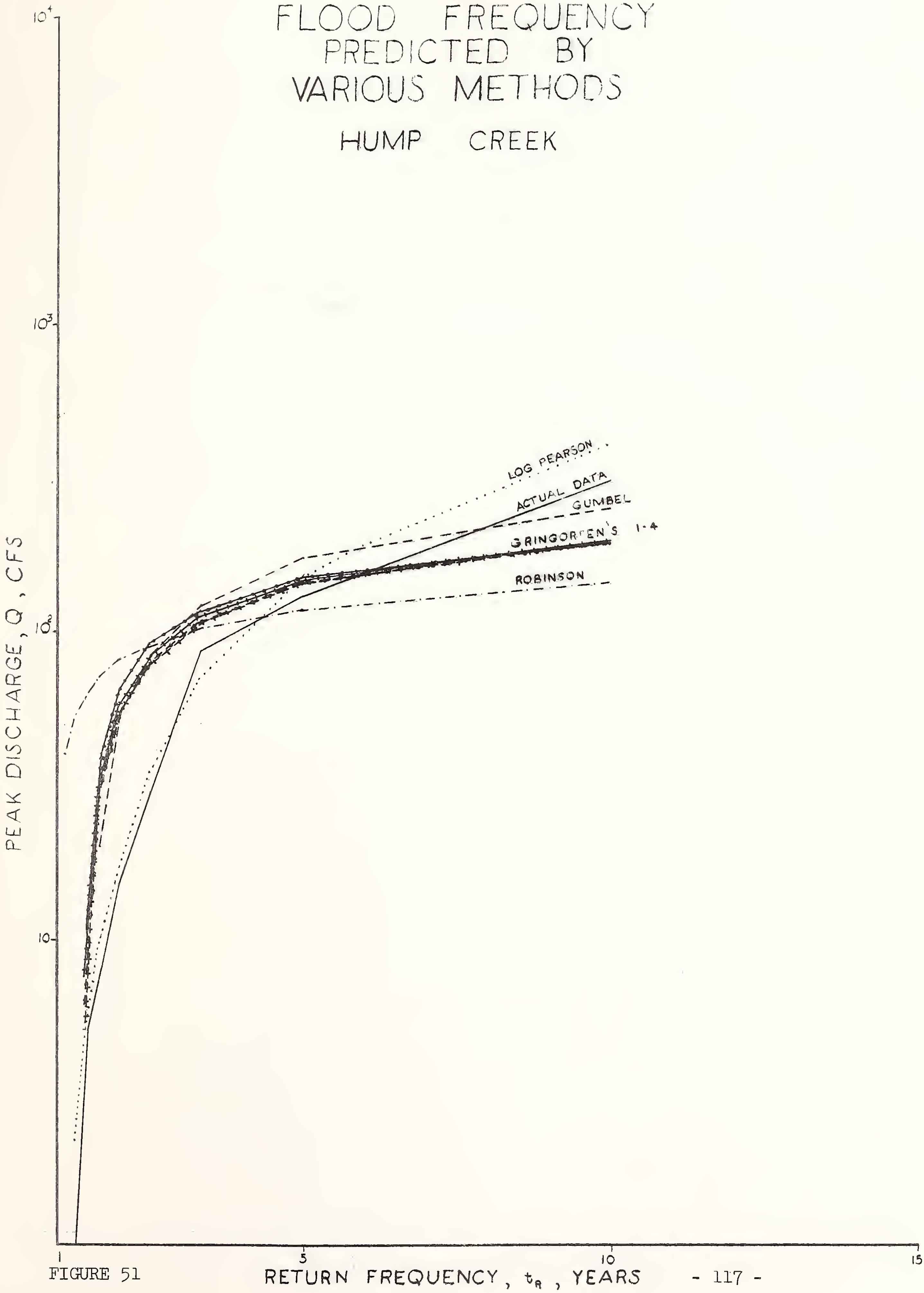

FLOOD FREQUENCY
PREDICTED BY
VARIOUS METHODS
EAST FORK DUCK CREEK
LOG PEARSON
ACTUAL DATA
ROBINSON
GUMBEL
GRINGORTEN'S 1-4
PEAK DISCHARGE, Q, CFS
10^4
10^3
10^2
10
1
5
10
15
RETURN FREQUENCY, t_R, YEARS

FIGURE 50



FLOOD FREQUENCY
PREDICTED BY
VARIOUS METHODS
HUMP CREEK
10^4
10^3
10^2
10
PEAK DISCHARGE, Q, CFS
LOG PEARSON
ACTUAL DATA
GUMBEL
GRINGORTEN'S 1-4
ROBINSON
1
5
10
15
RETURN FREQUENCY, t_R, YEARS

FIGURE 51

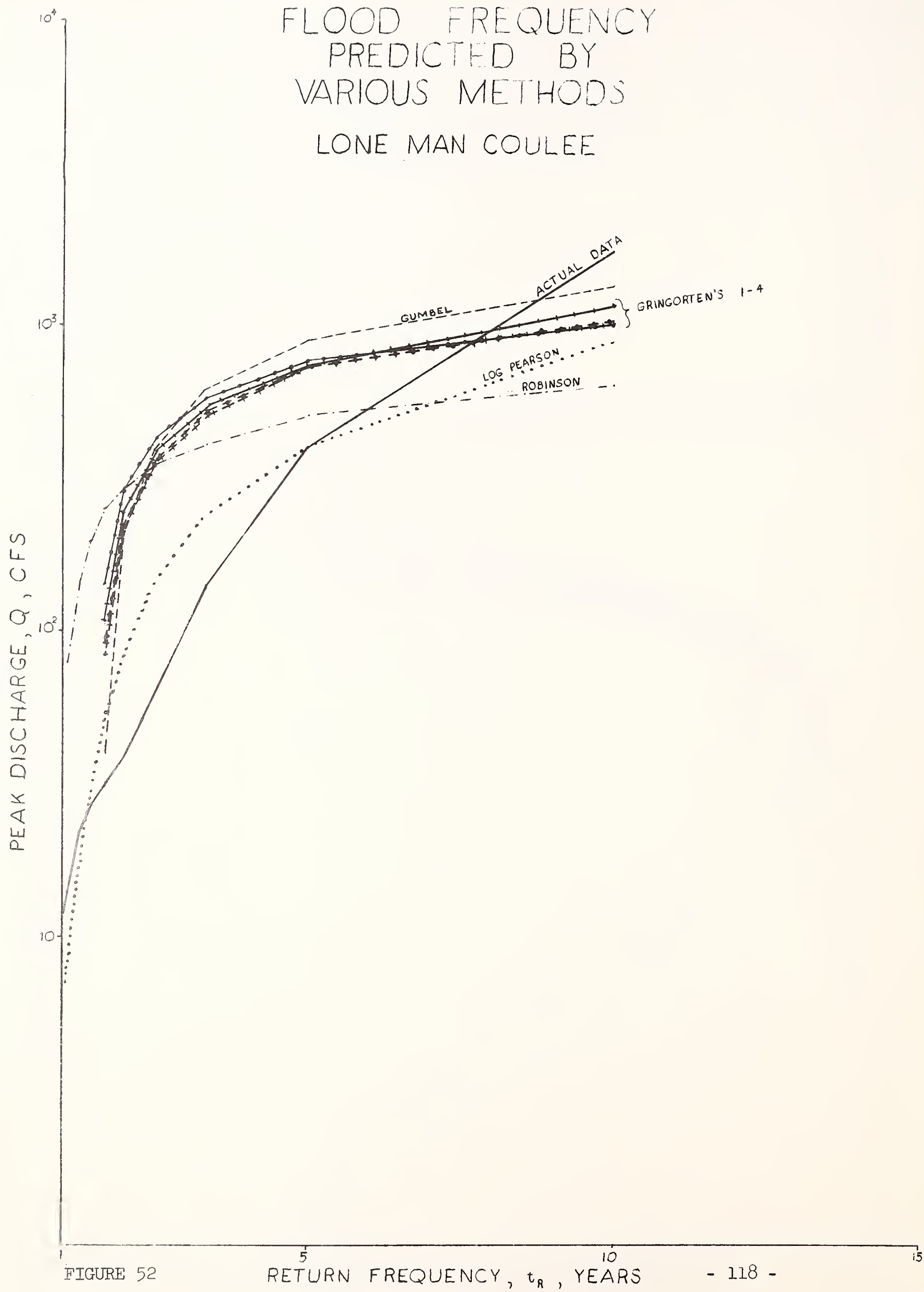

FLOOD FREQUENCY
PREDICTED BY
VARIOUS METHODS
LONE MAN COULEE
ACTUAL DATA
GUMBEL
GRINGORTEN'S 1-4
LOG PEARSON
ROBINSON
PEAK DISCHARGE, Q, CFS
RETURN FREQUENCY, t_R, YEARS
10^4
10^3
10^2
10
1
5
10
15

FIGURE 52

The rankings of the seven methods on the five watersheds from Tables VII and VIII were subject to a Friedman two-way classification test to ascertain whether there are significant differences among the methods, and whether there are significant differences among the response of the watersheds to the various fitting methods. The Friedman test involves the computation of Rank Chi-Square, using the sum of the ranks in each row, in the formula

$$\chi_r^2 = \frac{12}{rc(c+1)} \sum_i r_i^2 - 3r(c+1) \qquad (19)$$

where χ_r^2=Rank Chi-Square, to be compared against tabulated χ^2 values for desired probability and degrees of freedom (r-1)

r = number of rows

c = number of columns

r_i= sum of ranks in row i

Tables VII and VIII show computed Rank Chi-Square values, together with tabulated values for 1% probability at the specified degrees of freedom.

DISCUSSION

Table VII shows that when negative runoff predicitions were assigned the value zero the Gumbel method correlated best with recorded data on all five watersheds. The Gringorten methods generally ranked next best, although the Log Pearson Type III method ranked second best on two watersheds and sixth best on three watersheds. The sum of the rankings placed the Log-Pearson method tied for 4th and 5th place with Gringorten Type II method. The peak rainfall frequency-peak flow frequency method ranked poorest, probably owing to

TABLE VII: RESULTS OF ANALYSIS OF VARIANCE USING SEVEN METHODS AND FIVE WATERSHEDS

COEFFICIENTS OF DETERMINATION (R^2) AND RANKINGS TO SHOW WHICH METHOD CORRELATES BEST ON EACH WATERSHED

		Using Negative Predicted Runoff						Negative Predicted Runoffs Assigned the Value Zero					
	METHOD	LONE MAN	DUCK CREEK	E. FK. DUCK	HUMP CREEK	BACON CREEK	Total Rankings	LONE MAN	DUCK CREEK	E. FK. DUCK	HUMP CREEK	BACON CREEK	Total Rankings
#1	GUMBEL	.553 (4)	.933 (1)	.920 (1)	.773 (1)	.562 (4)	(11)	.715 (1)	.966 (1)	.943 (1)	.874 (1)	.713 (1)	(5)
#2	GRINGORTEN #1	.495 (6)	.864 (5)	.834 (5)	.686 (5)	.468 (6)	(27)	.593 (6)	.889 (5)	.856 (5)	.743 (5)	.589 (6)	(27)
#3	GRINGORTEN #2	.549 (5)	.891 (4)	.869 (4)	.730 (4)	.532 (5)	(22)	.637 (5)	.908 (4)	.883 (4)	.779 (4)	.638 (5)	(22)
#4	GRINGORTEN #3	.578 (3)	.901 (3)	.885 (3)	.753 (3)	.567 (3)	(15)	.658 (4)	.914 (3)	.895 (3)	.795 (3)	.662 (4)	(17)
#5	GRINGORTEN #4	.592 (2)	.905 (2)	.892 (2)	.762 (2)	.584 (2)	(10)	.668 (3)	.916 (2)	.900 (2)	.802 (2)	.674 (3)	(12)
#6	ROBINSON	.401 (7)	.401 (7)	.344 (7)	.435 (7)	.366 (7)	(35)	.401 (7)	.401 (7)	.344 (7)	.435 (7)	.366 (7)	(35)
#7	LOG-PEARSON TYPE 3	.713 (1)	.602 (6)	.726 (6)	.538 (6)	.703 (1)	(20)	.713 (2)	.602 (6)	.726 (6)	.538 (6)	.703 (2)	(22)

Using Negative Predicted Runoff:

Friedman Chi-Square$_{(6)}$ = 20.74

Chi-Square$_{(6)\ (.01)}$ = 16.8

Negative Predicted Runoffs Assigned the Value Zero:

Friedman Chi-Square$_{(6)}$ = 24.86

Chi-Square$_{(6)\ (.01)}$ = 16.8

Note: The values in this table are coefficients of determination (R^2). Larger numbers represent better correlation. Numbers in parenthesis indicate rankings (1 = best) in order by method for each watershed. Total rankings indicate sums of rankings added across for each method. The lowest total ranking value indicates the method that correlated best with the data from these five watersheds.

TABLE VIII: RESULTS OF ANALYSIS OF VARIANCE USING SEVEN METHODS AND FIVE WATERSHEDS

COEFFICIENTS OF DETERMINATION (R^2) TO SHOW WITH WHICH WATERSHED EACH METHOD CORRELATES BEST

	Using Negative Predicted Runoff								Negative Predicted Runoffs Assigned the Value Zero							
	Gumbel	Gringorten #1	Gringorten #2	Gringorten #3	Gringorten #4	Robinson	Log-Pearson	Total Rankings	Gumbel	Gringorten #1	Gringorten #2	Gringorten #3	Gringorten #4	Robinson	Log-Pearson	Total Rankings
Lone Man Coulee	.553 (5)	.495 (4)	.549 (4)	.578 (4)	.592 (4)	.401 (1.5)	.713 (2)	(24.5)	.715 (4)	.593 (4)	.637 (5)	.658 (5)	.668 (5)	.401 (1.5)	.715 (2)	(26.
Duck Creek	.933 (1)	.864 (1)	.891 (1)	.901 (1)	.905 (1)	.401 (1.5)	.602 (4)	(10.5)	.966 (1)	.889 (1)	.908 (1)	.914 (1)	.916 (1)	.401 (1.5)	.602 (4)	(10.
E. Fk. Duck Creek	.920 (2)	.834 (2)	.869 (2)	.885 (2)	.892 (2)	.344 (5)	.726 (1)	(16)	.943 (2)	.856 (2)	.883 (2)	.895 (2)	.900 (2)	.344 (5)	.726 (1)	(16)
Hump Creek (3)	.773 (3)	.686 (3)	.730 (3)	.753 (3)	.762 (3)	.435 (3)	.538 (5)	(23)	.874 (3)	.743 (3)	.779 (3)	.795 (3)	.802 (3)	.435 (3)	.538 (5)	(23)
Bacon Creek	.562 (4)	.468 (5)	.532 (5)	.567 (5)	.584 (5)	.366 (4)	.703 (3)	(31)	.713 (5)	.589 (5)	.638 (4)	.662 (4)	.674 (4)	.366 (4)	.703 (3)	(29)

Friedman Chi-Square$_{(4)}$ = 14.37

Chi-Square$_{(4)}$ (.01) = 13.30

Friedman Chi-Square$_{(4)}$ = 13.34

Chi-Square$_{(4)}$ (.01) = 13.30

Note: The values in this table are coefficients of determination (R^2). Larger numbers represent better correlations. Numbers in parenthesis indicate rankings (1 = best) in order by watershed for each method. Total rankings indicate sums of rankings added across for each watershed. The lowest total ranking value indicates the watershed that correlated best with all seven methods.

inaccurate evaluation of R_i, and no adjustment in D_i or F_i for lower return periods.

When negative runoffs were permitted to remain in the predictions, Table VII shows that the Gumbel method was best on three watersheds and 4th best on 2. The Log-Pearson Type III method was best on two watersheds and 6th best on 3. The sume of the rankings placed the Gringorten Type IV method best, followed by Gumbel, Gringorten Type II and Log-Pearson Type III in descending order. The peak rainfall frequency-peak flow frequency method was again poorest.

All the computed values for Rank Chi-Square were larger than the corresponding tabulated Chi-Square values at the 1 percent probability. The conclusion therefore is that there are indeed significant differences in the correlations obtained with the seven methods, and also that there are significant differences in the way the five watersheds respond to the various fitting methods.

CONCLUSIONS

The results reported herein indicate that of the seven methods, the extreme value (Gumbel) technique generally did the best job of predicting peak discharges on the five project watersheds, although when negative predictions were permitted this method did a poorer job of predicting flows at Bacon Creek and Lone Man Coulee. The Log-Pearson Type III method, which is now required for use in frequency studies by all federal agencies did a relatively poor job of predicting flows on these watersheds. The peak rainfall

frequency-peak flow frequency performed poorest of all the methods, but this is believed due to lack of data from which to adequately define the terms in the prediction equation.

In view of the statistical difference found in the five watersheds it must be concluded that no single method is adequate for use throughout eastern Montana. In fact, further analyses were made using Duck Creek and East Fork of Duck Creek data. Since one of these watersheds is a tributary of the other it might seem that these watersheds at least would respond similarly. But two tests, the Mann-Whitney modification of the Wilcoxson test, and the Wald-Wolfowitz Runs test both gave a significant difference in the two basins.

SUMMARY

Statistical tests to determine relative goodness of seven peak flow prediction methods on five project watersheds have been presented and discussed.

CHAPTER IX

STUDY OF ANNUAL PEAK DISCHARGES FROM SMALL DRAINAGE AREAS

Annual peak discharges collected from 228 small watersheds by the U.S. Geological Survey in cooperation with the Montana State Highway Commission have been studied to determine whether watersheds in geographic proximity to each other behave similarly hydrologically. In those geographical areas where such is the case it should be possible to reduce the total number of gaging stations required to establish the hydrologic properties of the area. This chapter reports the findings of this study.

BACKGROUND

The station-year method of analyzing rainfall records was proposed as early as 1936 (see Linsley, Kohler, Paulhus, 1958). The method assumes that records from several stations in a limited area can be combined and treated as a single record whose length is equal to the sum of the individual records. The reliability of the analysis is determined by the amount of dependence or independence between the stations in the network. If the stations are so spaced that one and only one station measures each storm, the data are entirely independent; but if more than one station measures each storm, then there are actually fewer independent stations and the validity of the method is questionable. The method has been the subject of considerable discussion and some controversy, but it is generally believed to be valid provided the stations are truly independent, and located within a meteorologically homogeneous area.

Within a hydrologically homogeneous area, and subject to the same limitations on independence of records, the method should be equally valid when applied to streamflow records; but no reference in the literature was found to indicate that the procedure had been applied to streamflow data.

A recurring question in connection with the U.S. Geological Survey--Montana Highway Commission cooperative program to investigate the magnitude and frequency of floods from small Montana watersheds is whether or not all of the more than 200 gaging stations should be continued, now that several years of record at each station have been obtained. If it could be established that two or more independent watersheds are located in the same hydrologic unit, then it should be possible to pool the data from all watersheds in the unit, creating a record perhaps several times as long as that from any single station, and thereby reduce significantly the error associated in predicting peak flow magnitudes and frequencies. Within such a hydrologic unit it might very well be decided that collection of further data is not necessary.

An analysis of variance can be made to establish whether or not certain watersheds lie in a single hydrologic area, and whether or not it is valid to combine data into a single record. This analysis cannot, however, test for independence of record.

PROCEDURE

The watersheds included in the cooperative small watershed program were grouped into 48 tentative hydrologic units, using geographical proximity, same or adjacent drainage basin, and comparable elevation as criteria for

making the groupings. The annual peak discharges recorded from these watersheds by the U.S. Geological Survey were inspected to ascertain whether, within each area, the data were independent. The inspection showed that frequently a single storm produced the peak annual discharge on two or more watersheds. But rarely were these discharges comparable in return period. It is believed therefore that with few exceptions the data from the water sheds can be considered independent.

Of the 228 watersheds in the cooperative program, 29 were excluded from any group because there were inadequate streamflow records available, or because they seemed to be hydrologically isolated. The hydrologic groupings are shown on a map of Montana, Figure 53. Numbers on the map are Geological Survey watershed identification numbers. The watersheds are identified in Appendix H.

For each watershed, sample mean and standard deviation were computed for the recorded annual peak flows; 90% confidence limits were computed for the mean by using the Student's t test, and an upper limit for the standard deviation at the 90% probability level was computed using a Chi-Square test. (These tests have been described earlier, in Chapter II). Results are tabulated in Appendix H.

Within each of the 48 geographic units shown in Figure 53, recorded annual peak flows at each station were normalized (reduced to flow per square mile of drainage area), and the normalized means and standard deviations were subjected to an F test to determine whether at the 95 percent confidence level the watersheds are statistically different from each other. (The F test was

described earlier, in Chapter II). Results of this analysis are tabulated in Appendix H and are shown on Figure 53 where geographic units in which watersheds are statistically different are shaded.

For those areas which were found statistically to be homogeneous units, pooled mean and standard deviation were computed, and these values are tabulated for each watershed in Appendix H.

DISCUSSION

Twenty seven of the 48 geographic areas tested were found not to behave as hydrologic units. Only one of the areas west of the continental divide behaved as a unit; east of the divide most of the areas in the Missouri and Yellowstone headwaters and those in northern Montana behaved as hydrologic units and data from several watersheds can be pooled.

Those areas which did not behave as hydrologic units might now be re-examined dividing each area into smaller subdivisions and again testing for hydrologic similarity; or the areas might be regrouped placing some watersheds from 2 or 3 areas into one group and testing for similarity. A few such regroupings were tried without success, but a systematic or extensive program of regrouping has not been attempted.

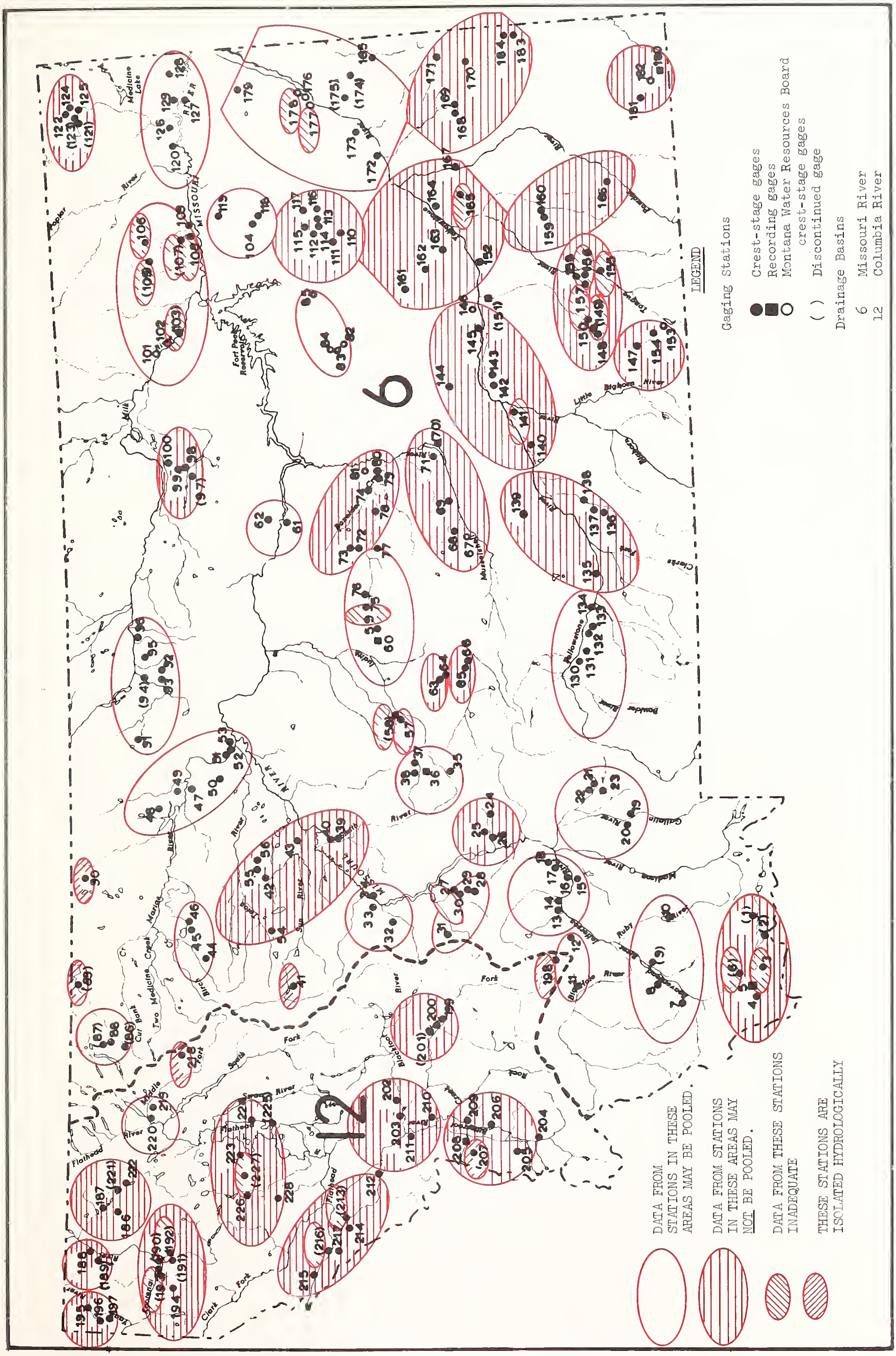

LEGEND
Gaging Stations
Crest-stage gages
Recording gages
Montana Water Resources Board crest-stage gages
( ) Discontinued gage
Drainage Basins
6 Missouri River
12 Columbia River
DATA FROM STATIONS IN THESE AREAS MAY BE POOLED.
DATA FROM STATIONS IN THESE AREAS MAY NOT BE POOLED.
DATA FROM THESE STATIONS INADEQUATE
THESE STATIONS ARE ISOLATED HYDROLOGICALLY

FIGURE 53

CONCLUSIONS

Although this study has not exhausted all possibilities, hydrologically homogeneous units have been delineated in many areas of the state. Within these areas it is believed that recorded data are essentially independent, and that predictions of peak discharge magnitudes and frequencies may be vastly improved by pooling data from all the watersheds. This is evidenced by the dramatically smaller ranges on confidence limits for means and the lowered upper bound on standard deviation which are shown in Appendix H.

It appears reasonable to conclude that to obtain the greatest benefits from the cooperative small drainage area program in Montana it would now be desirable to relocate some of the crest stage gages from watersheds located in delineated hydrologic units to some of the many areas of the state where no streamflow measurements are presently being obtained. At least one or more gaging stations within each hydrologic unit should be maintained, to obtain index measurements which should be transferable to all watersheds in the unit. Up to 60 gages might be available for relocation

SUMMARY

Twenty-one hydrologically homogeneous units have been delineated in Montana within which it is believed streamflow data from several watersheds may be pooled into one record to improve predictions of peak flow magnitudes and frequencies. To maximize benefits from the cooperative small watershed program in Montana some of the crest stage gages could now be relocated into areas of the State where no records are available.

CHAPTER X

LENGTH OF RECORD AS IT AFFECTS PEAK FLOW PREDICTIONS

Four watersheds which are included in the U.S. Geological Survey-Montana Highway Commission cooperative small drainage area program were studied to see what differences occurred in peak flow magnitude and frequency predictions as a result of changing length of record. Three frequency distributions were used in the study.

PROCEDURE

The most frequently used peak flow prediction methods are usually considered inadequate when applied to records of less than 10 or 15 years in length. To study effect of record length on predictions, therefore, it was necessary to select watersheds having streamflow record lengths at least twice as long as the acceptable minimum. Four watersheds which are included in the small drainage area program were used in this study. Each has a record length in excess of 30 years. Three of the four are much larger in area than 100 square miles, but is is believed that findings relative to record length on these watersheds will be valid for smaller watersheds as well. Watersheds selected are listed in Table IX. Watershed numbers shown in the table refer to U.S. Geological Survey identification numbers; these numbers are used on the location map, Figure 53.

TABLE IX.

Watershed Number	Name	Area Sq.Mi.	Record Length yrs.
7	Grasshopper Creek near Dillon	348	33
78	McDonald Creek at Winnett	421	31
138	Pryor Creek near Billings	435	44
209	Burnt Fork Creek near Stevensville	74	36

Three commonly used frequency distributions were used in the study: extreme value (Gumbel) method; log-normal (Chow) method; and log-Pearson Type III method. For each watershed and each method, peak discharge magnitudes and frequencies were predicted using each half of the record separately, and using the entire record. The results were graphed, Figures 54 to 65. Data and computations are shown in Appendix J.

DISCUSSION

Examination of Figures 54 to 65 shows that no one method gave superior results on all four watersheds; and significant differences are noted when comparing predictions made with one half of the data with predictions made using all the data.

The Gumbel method gave best results of the three methods tried on McDonald Creek, but for the other three watersheds the second-half data fit

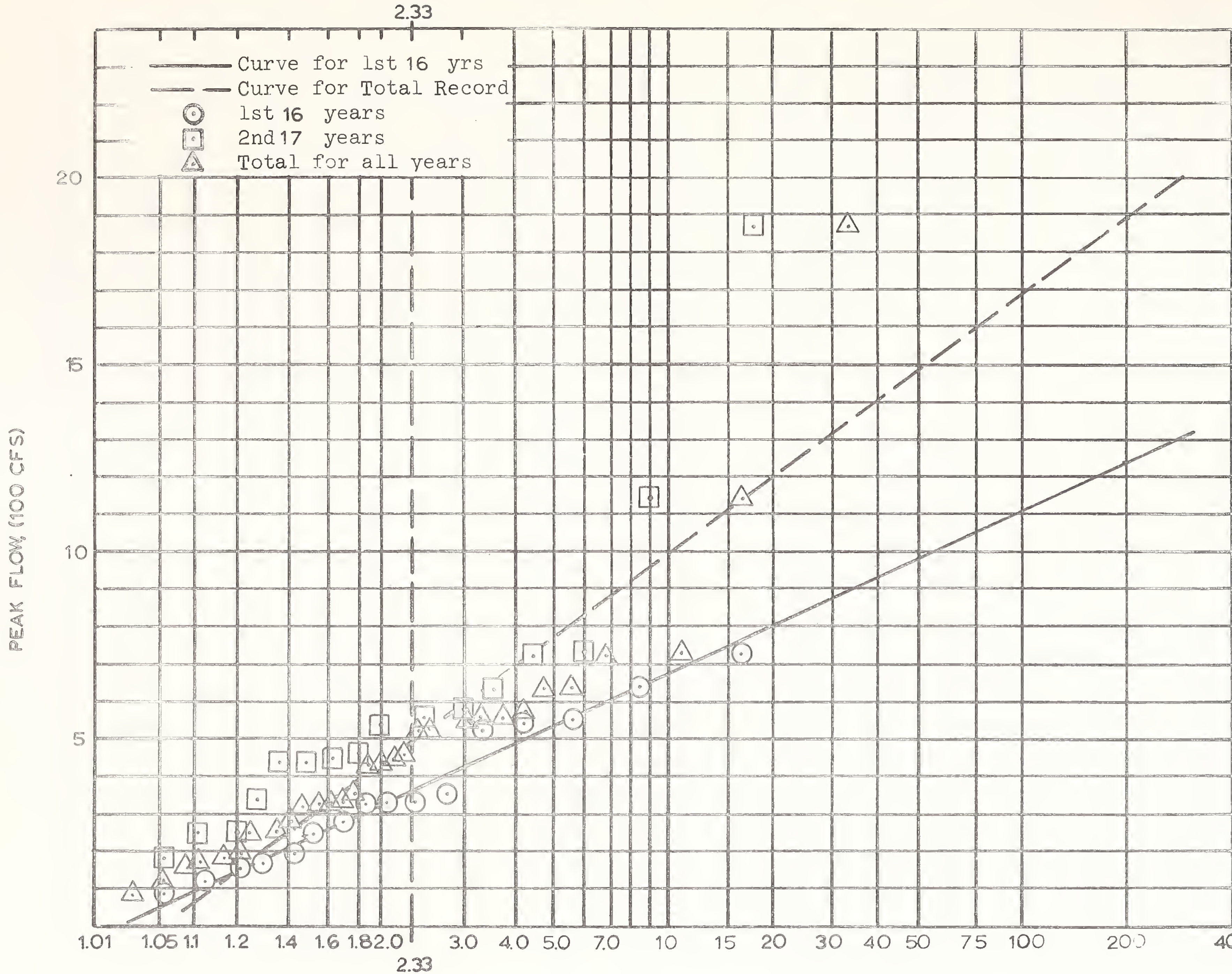


FIGURE 54 -- Frequency Curve of Annual Floods at Grasshopper Creek (Gumbel Method)

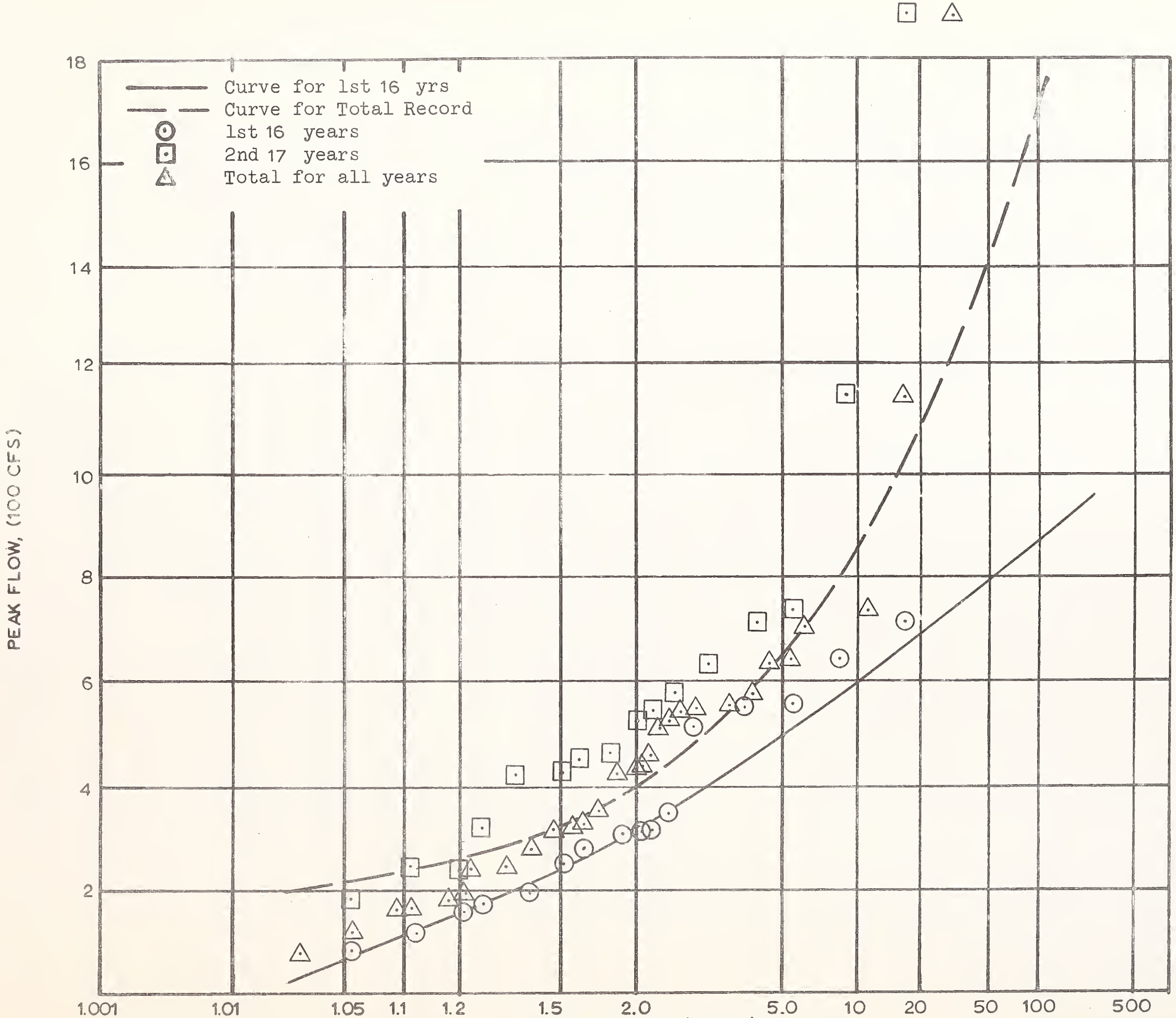


FIGURE 55 -- Frequency Curve of Annual Floods at Grasshopper Creek (Log-Normal Method)

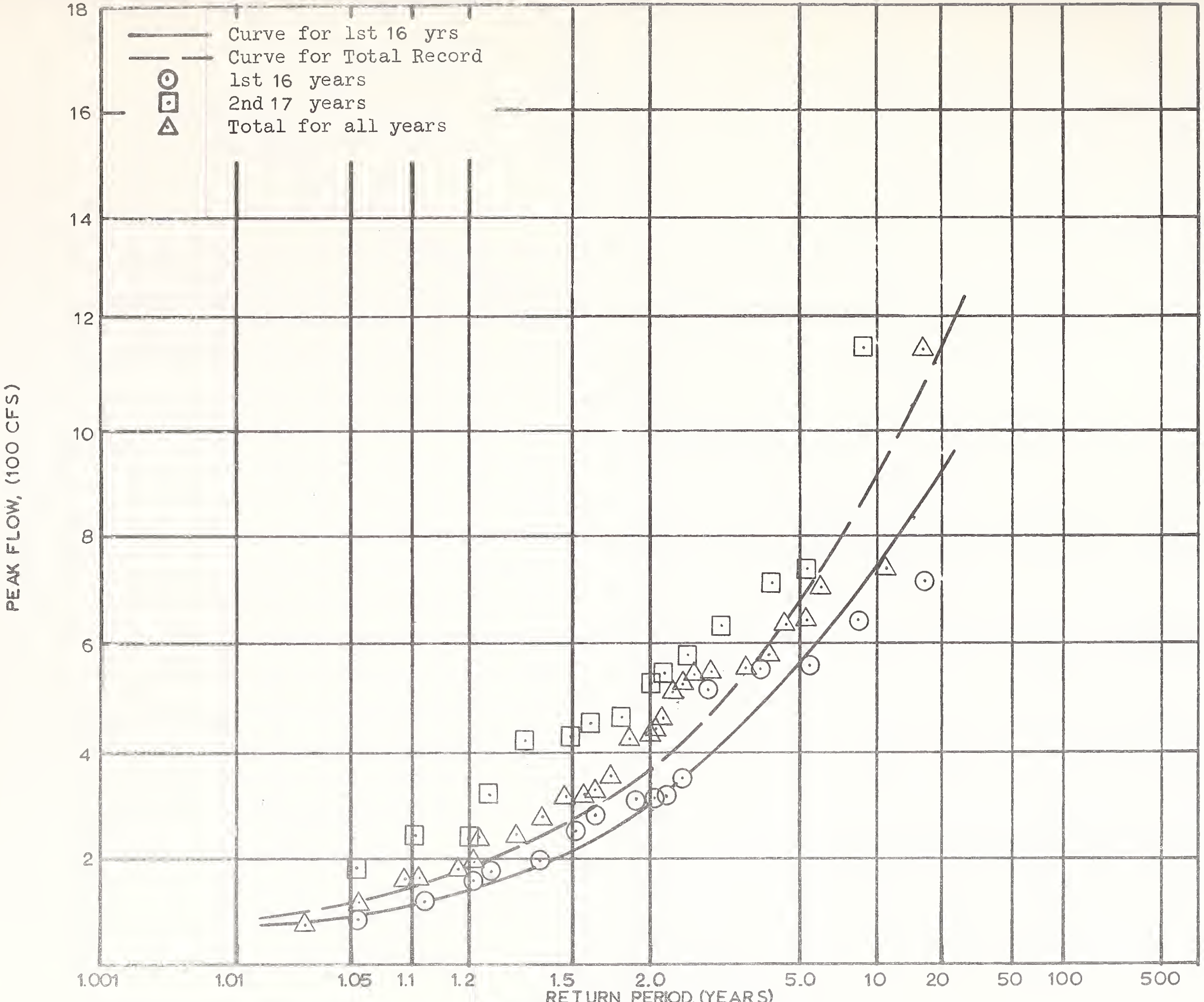


FIGURE 56 -- Frequency Curve of Annual Floods at Grasshopper Creek
(Log-Pearson Type III Method)

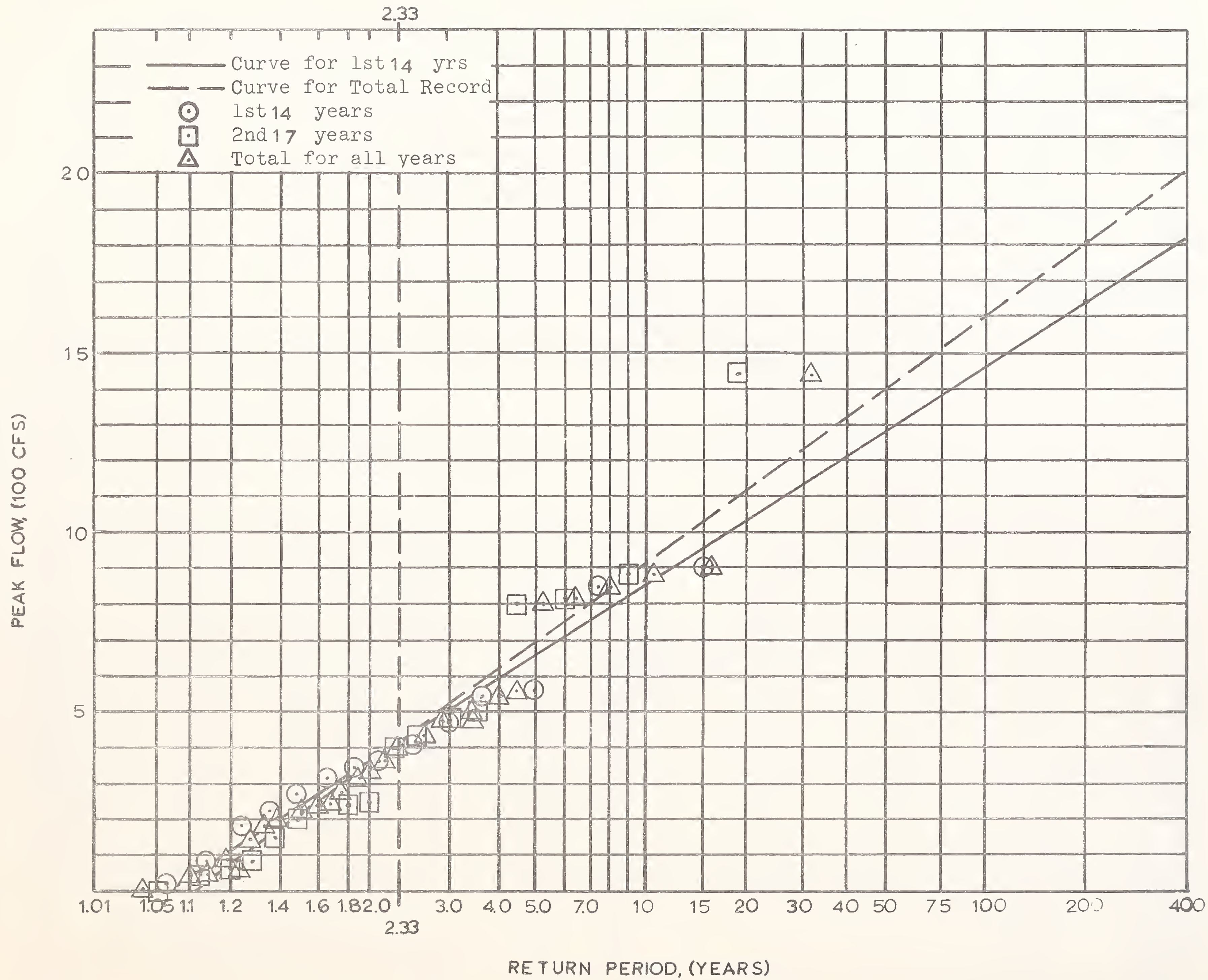


FIGURE 57 -- Frequency Curve of Annual Floods at McDonald Creek
(Gumbel Method)

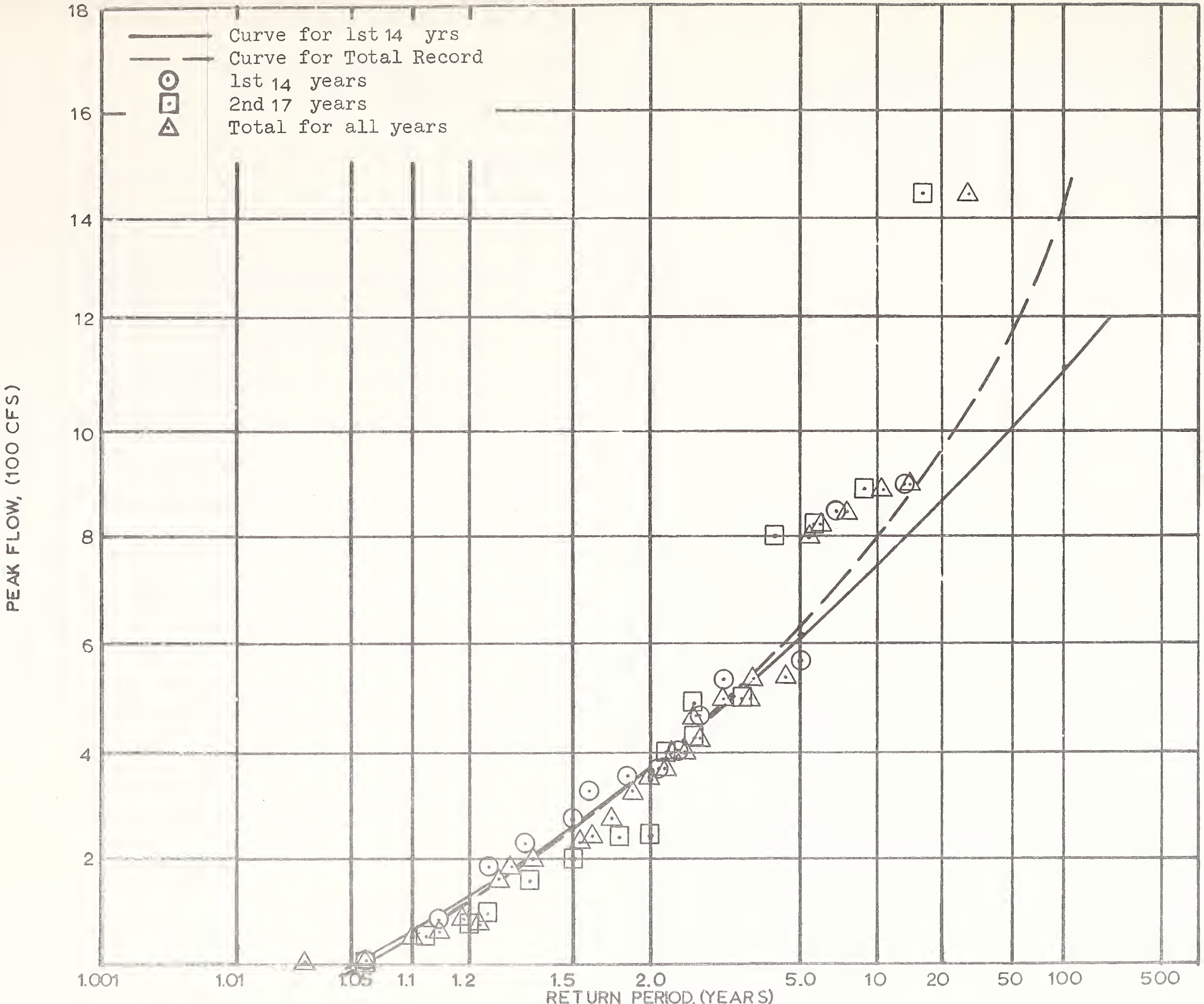


FIGURE 58 -- Frequency Curve of Annual Floods at McDonald Creek
(Log-Normal Method)

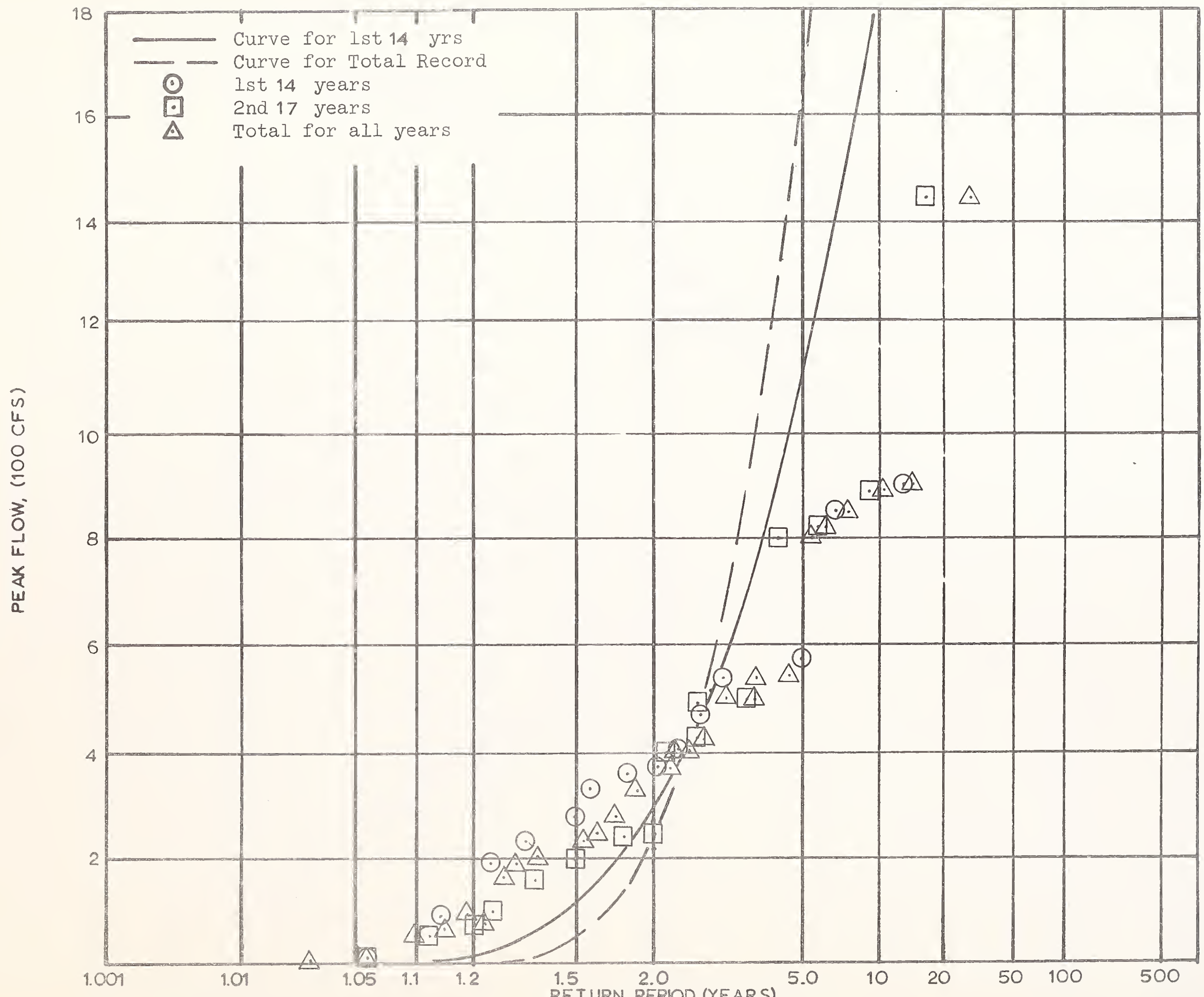


FIGURE 59 -- Frequency Curve of Annual Floods at McDonald Creek
(Log-Pearson Type III Method)

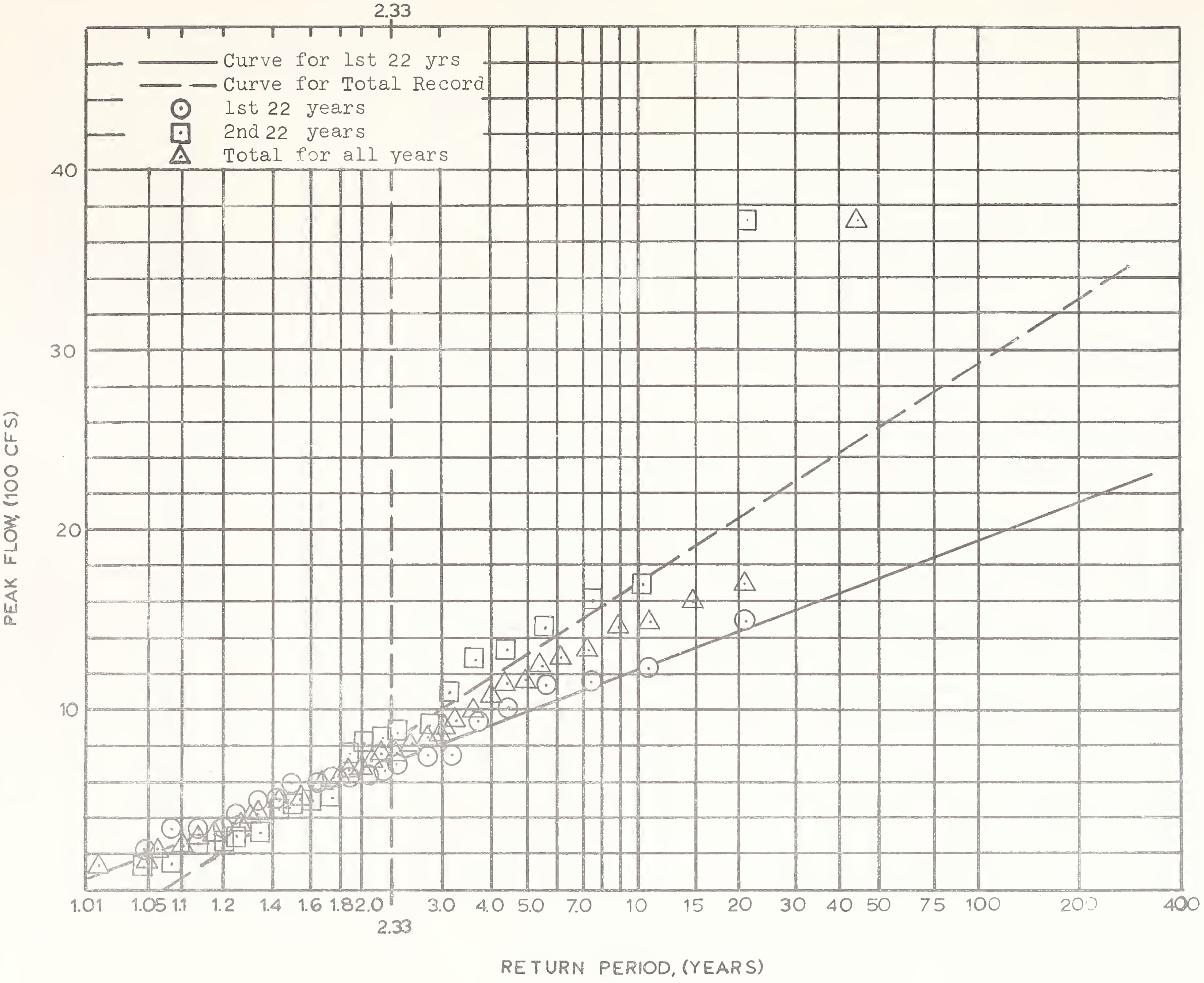


FIGURE 60 -- Frequency Curve of Annual Floods at Pryor Creek
(Gumbel Method)

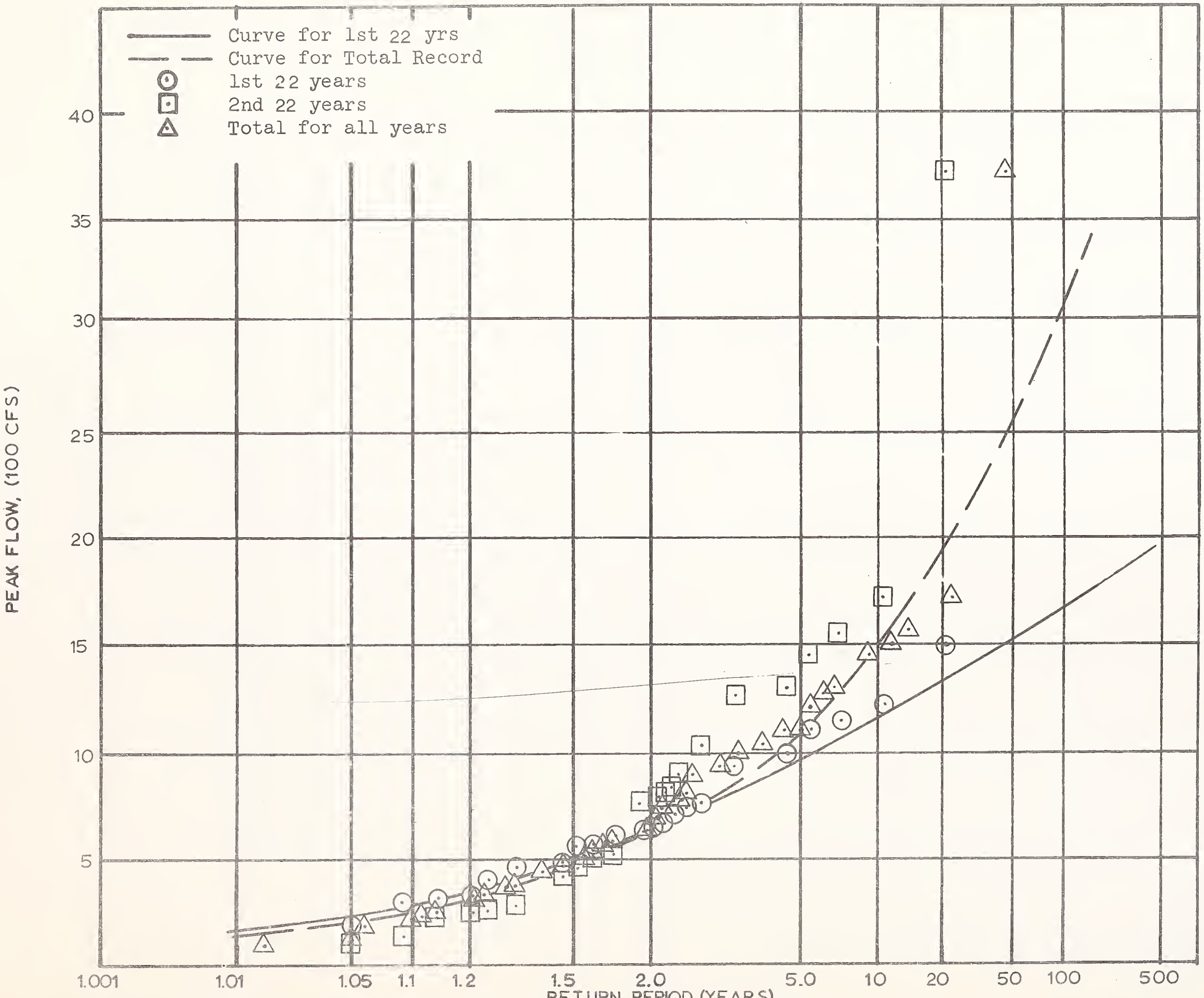


FIGURE 61 -- Frequency Curve of Annual Floods at Pryor Creek
(Log-Normal Method)

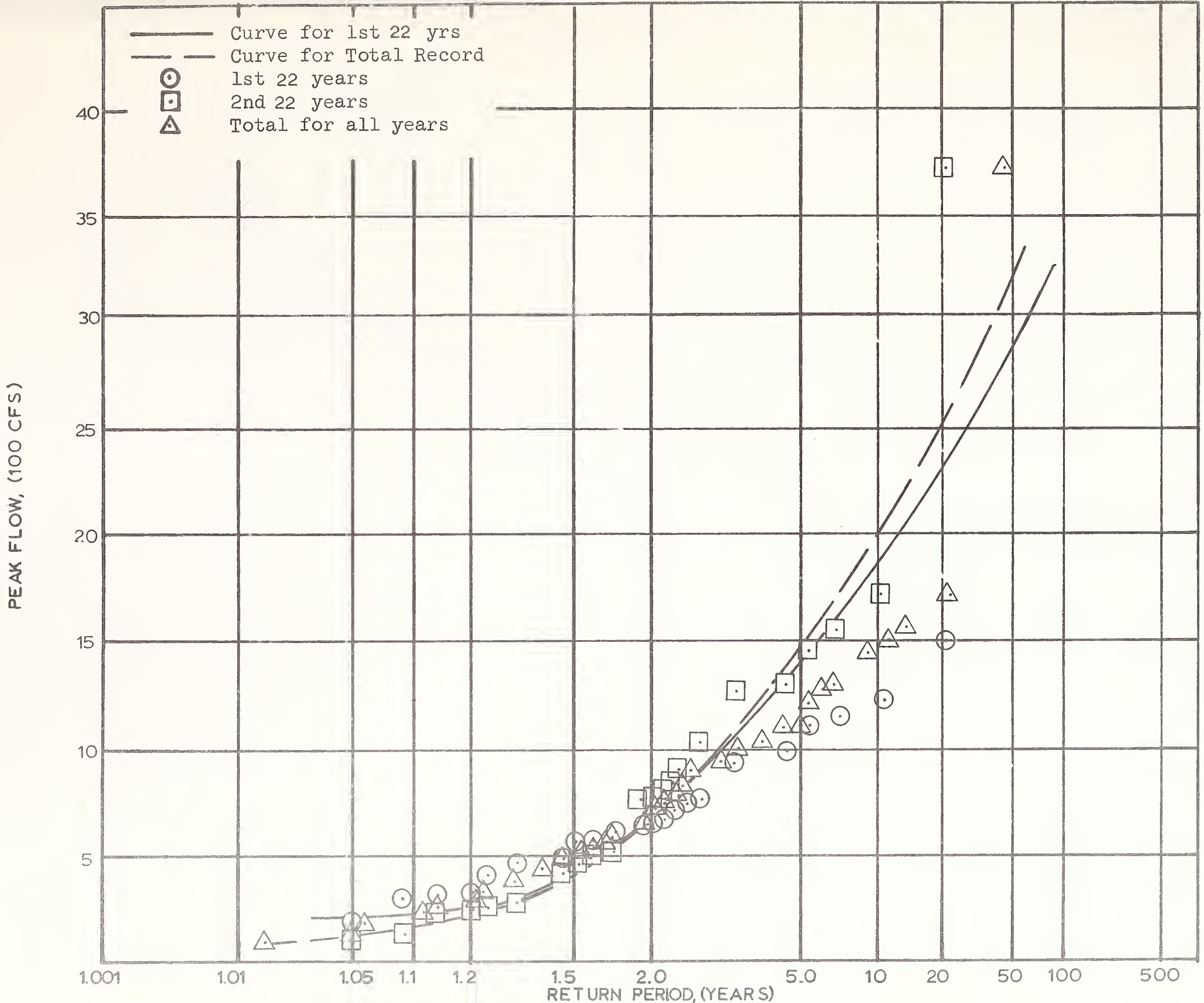


FIGURE 62 -- Frequency Curve of Annual Floods at Pryor Creek
(Log-Pearson Type III Method)

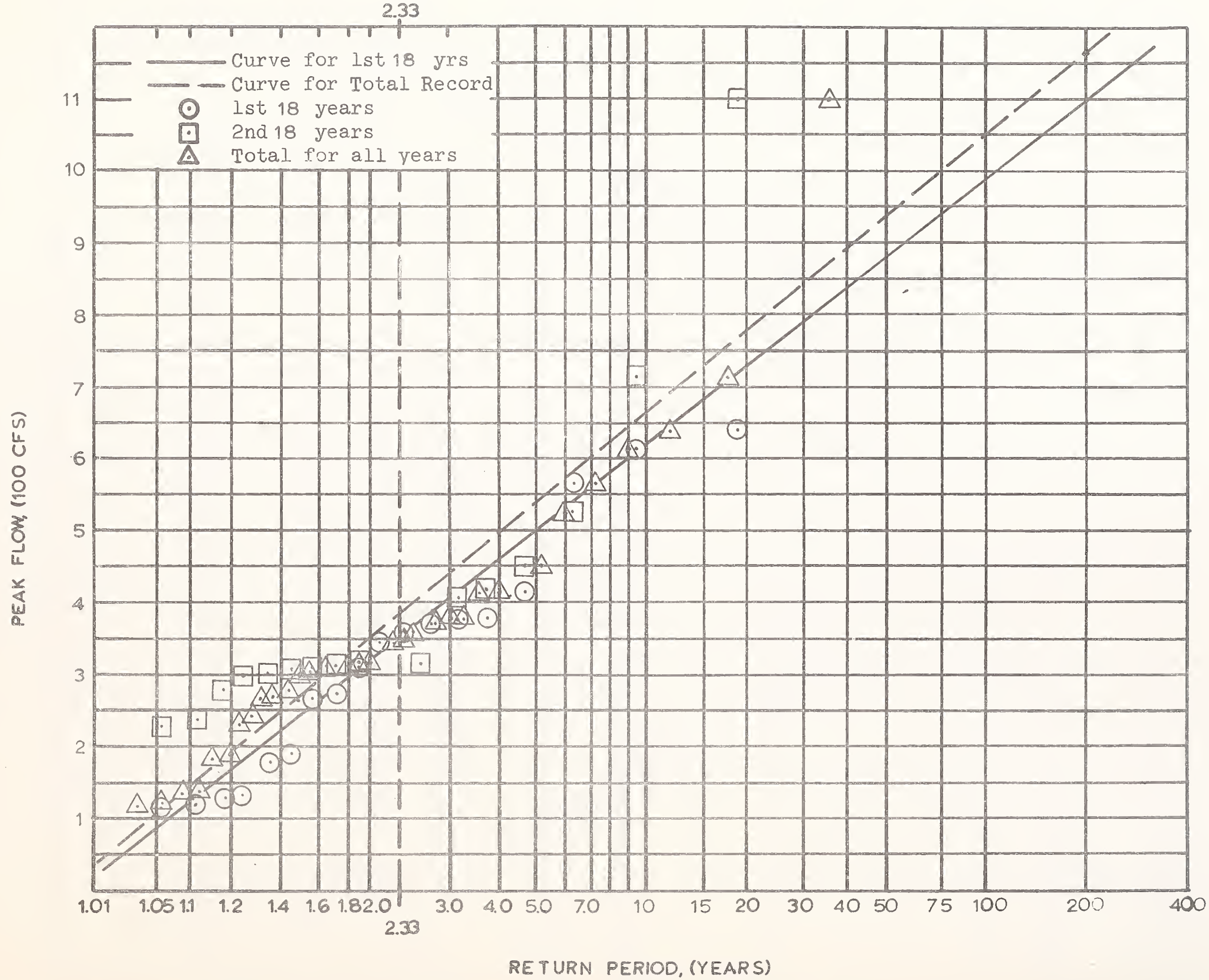


FIGURE 63 -- Frequency Curve of Annual Floods at Burnt Fork Creek (Gumbel Method)

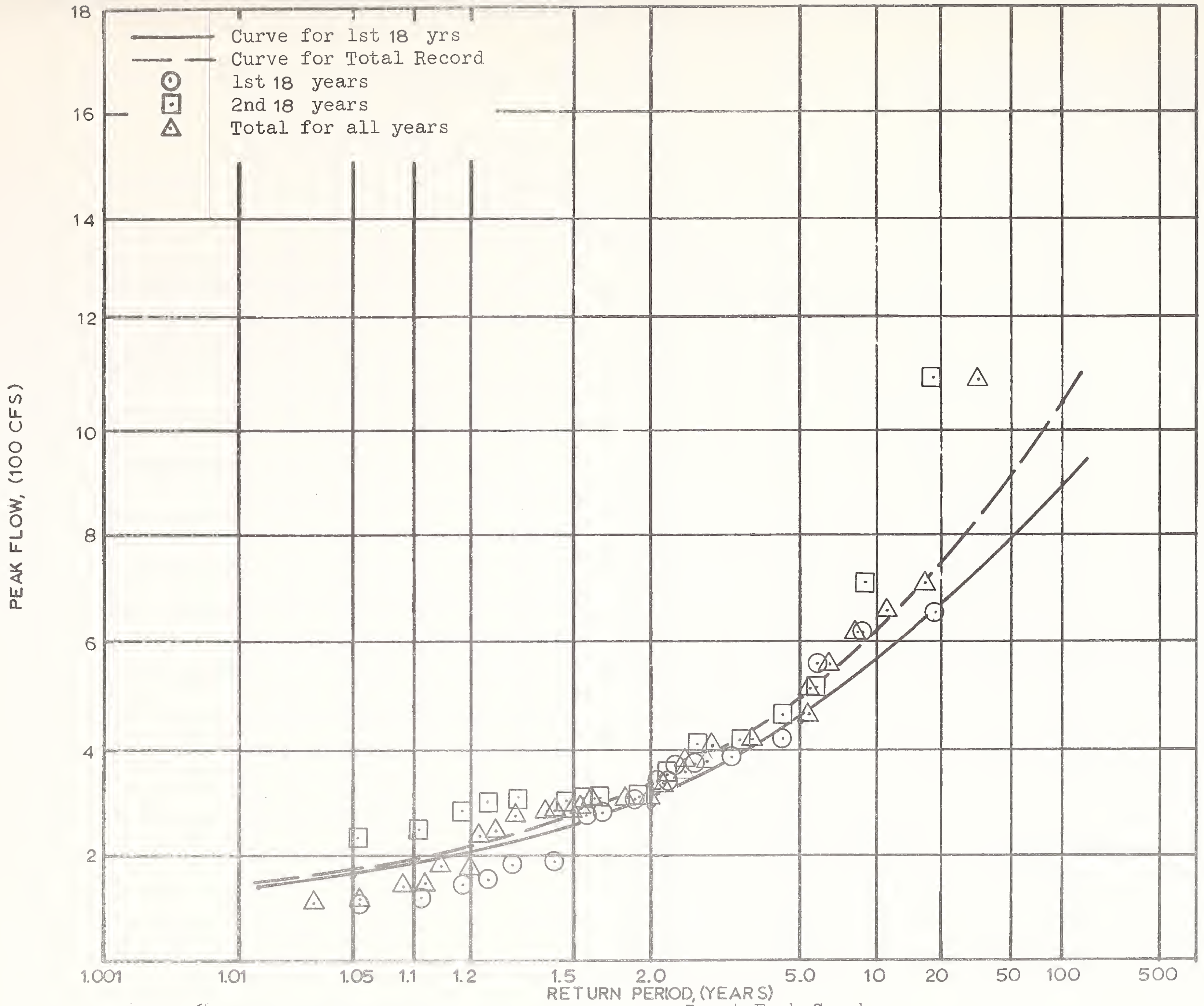


FIGURE 64 -- Frequency Curve of Annual Floods at Burnt Fork Creek
(Log-Normal Method)

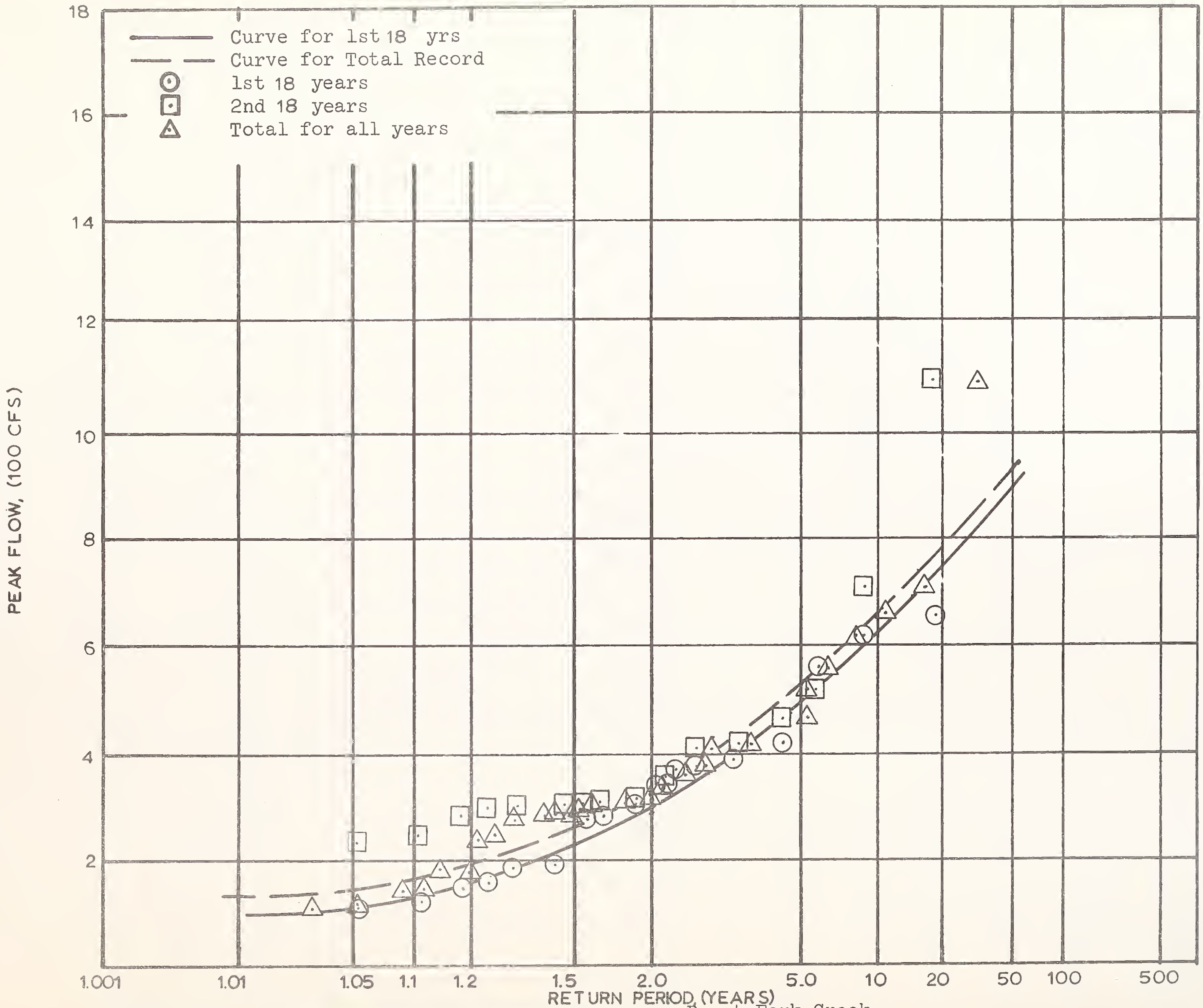


FIGURE 65 -- Frequency Curve of Annual Floods at Burnt Fork Creek
(Log-Pearson Type III Method)

the curve predicted from the earlier data poorly. On two of the watersheds (Pryor Creek and Grasshopper Creek) the fitting curve using the first-half data and the fitting curve using all the data diverged greatly at the 50-year frequency interval. On Burnt Fork Creek the Gumbel method produced nearly parallel curves whether using first-half data or all the data, but on the other three watersheds the corresponding curves are not parallel, and cross each other at approximately the 1.2 to 2.0 year frequency interval.

The log-normal method was not superior on any of the four watersheds. In each case the second-half data fit the curve predicted from the first-half data poorly. The fitting curves using the first-half data and all the data diverged badly on all watersheds except Burnt Fork Creek. With the Exception of Burnt Fork Creek the fitting curves crossed each other at approximately the 1.0 to 2.5 year frequency interval.

The Log-Pearson Type III method was the best method tried for Pryor Creek; however, on the other three watersheds the second-half data fit the curve from the first-half data poorly. On three of the watersheds, however, the fitting curve using the first-half data compared quite well with the fitting curve using all the data. The curves diverged badly only on Grasshopper Creek. On two of the watersheds, McDonald Creek and Pryor Creek, the fitting curves crossed each other between the 3.1 to 3.3 year frequency interval.

CONCLUSIONS

Considering the fitting curves obtained when using the first-half data as compared to the curve obtained when using all the data, it appears that the Log-Pearson Type III method is most satisfactory; the divergence between the curves at the 50-year frequency interval was satisfactory on three of the four watersheds. Comparable curves using the Gumbel method gave satisfactory results on two of the four watersheds, while the log-normal method was satisfactory on only one watershed.

Conclusions from this study are that no single method is satisfactory for prediction of peak flow magnitudes and frequencies on all watersheds; and that great discrepancy can be expected when predicting peak flows at the 50-year return period from records as short as 10 or 15 years.

SUMMARY

Results of a study of streamflow record length, using four watersheds and three frequency distribution methods have been discussed.

CHAPTER XI

PHOTOGRAMMETRIC STUDIES

Reference has been made earlier (Chapter III) to the fact that aerial photographs were taken of each of the Project watersheds three times during the study. Photos of Hump Creek and adjacent drainages were studied stereoscopically to see whether such analyses might help in evaluating drainage characteristics.

Several northward-flowing tributaries enter the Yellowstone River from the south between Big Timber and Reed Point (about 30 river miles). These tributaries mostly drain small watersheds. Included are the Boulder River (since it drains 523 square miles it can hardly be called a "small" watershed), Upper and Lower Deer Creeks, Bridger Creek (61 square miles), Work Creek (32 square miles) and Hump Creek (7.61 square miles). All these creeks flow almost due north. East of Hump Creek there is a sudden shift in direction of the drainages. Whistle Creek flows northeasterly, while Sectionhouse Creek and Countrymen Creek flow nearly east, as do most of the Yellowstone tributaries from Reed Point to Columbus, down to and including the Stillwater River. These drainages are shown on the map, Figure 66, and also appear in aerial photos in Appendix B (Figures B-5 and B-6).

The predominant geologic formation in the Hump Creek area is the Fort Union, an extremely thick formation which contains beds of impermeable clay shale alternately with permeable sandstone. The beds all have a shallow dip to the northeast. Hump Creek, Work Creek, and the other streams to the west have breached one or more of the bedding layers, and therefore have exposed

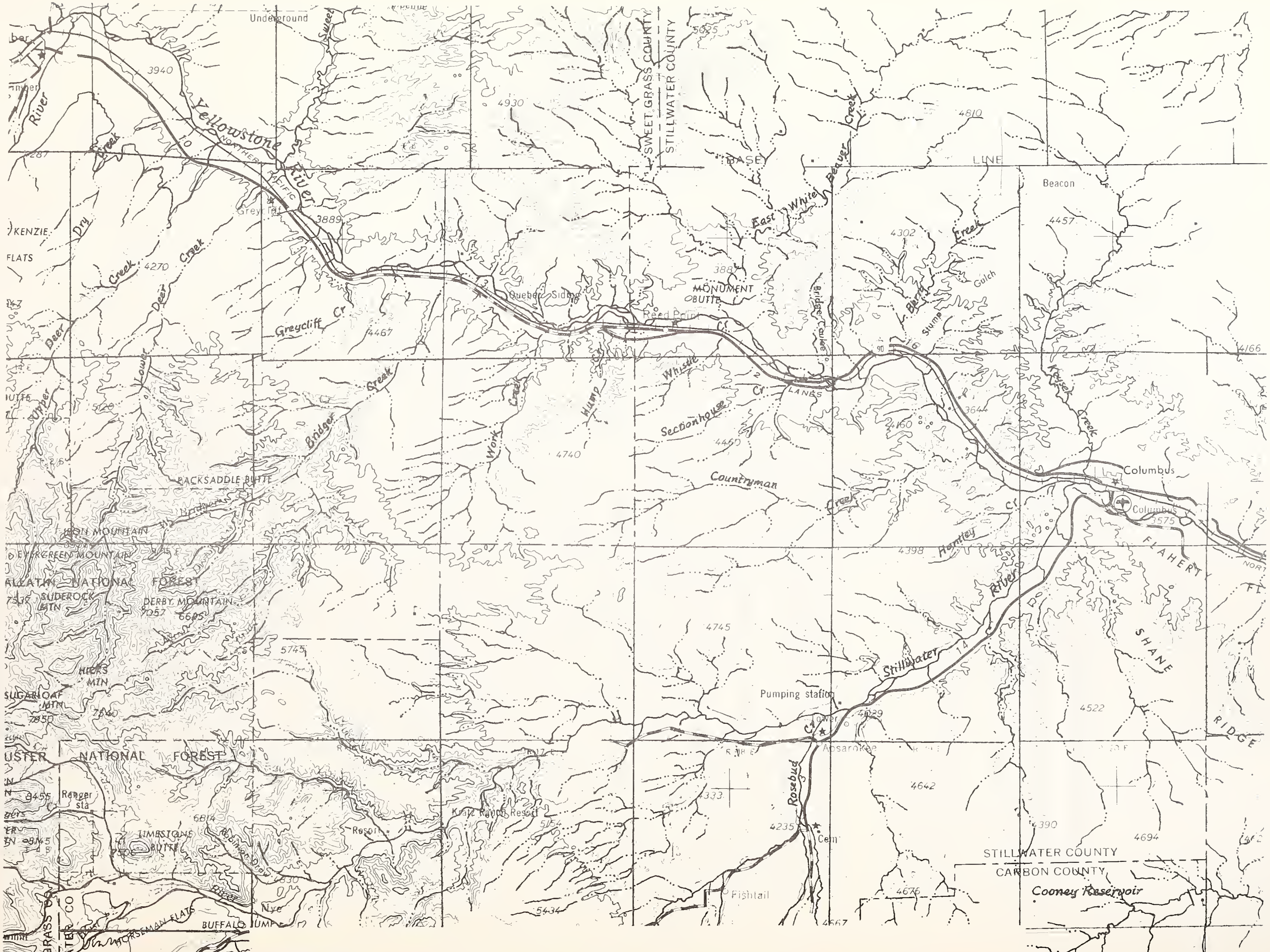


FIGURE 66 -- Map of Yellowstone River between Big Timber and Columbus

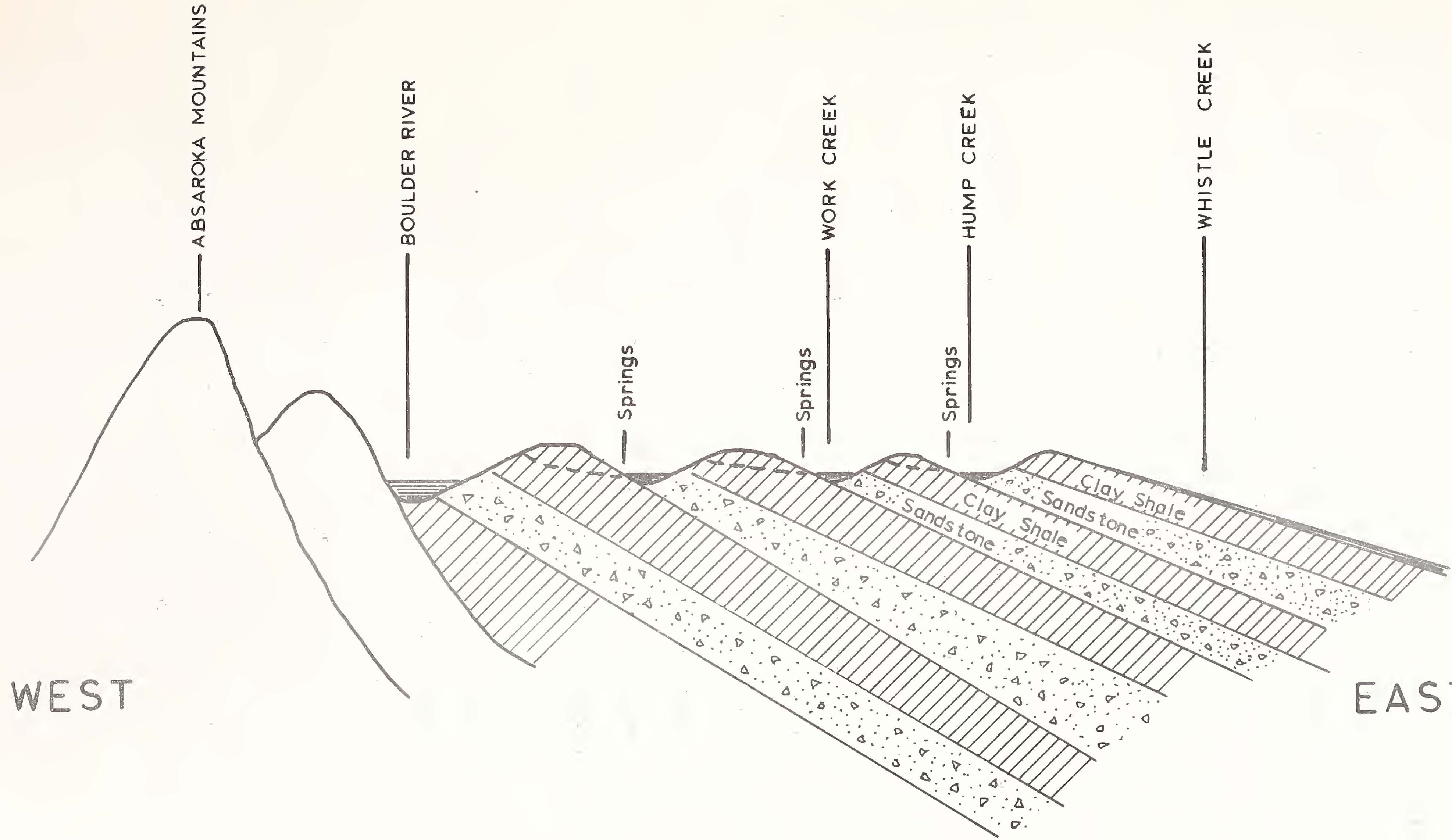


FIGURE 67 -- Cross-section of Fort Union formation south of the Yellowstone River. (Schematic, not to scale).

outcroppings of sandstone and shale on the eastern slopes of the watersheds. Headward erosion is occurring rapidly on these watersheds, which are quite steep. The streams to the east of Hump Creek flow parallel to the dip of the formation and do not exhibit significant erosion. Figure 67 shows an east-west cross-section of the formations. Aerial photos B-5 and B-6 clearly indicate the dip of the formations, and show the extent of the headward erosion.

Hump Creek and the streams to the west lose large quantities of water to the permeable beds underlying them. Each watershed picks up small quantities of water from springs on the western slopes of the basins which has percolated through from the next drainage to the west (Figure 67) but these springs are small and do not contribute significantly to surface runoff. Water which infiltrates into the permeable sandstone layers is carried under drainages lying to the east, and probably under the Yellowstone itself. This subsurface water does not reappear as surface flow anywhere in the vicinity, and perhaps not even in Montana. Snowmelt from the Absaroka mountains is captured by the Boulder River far to the west. Water percolating into permeable layers in the Boulder River drainage flows as subsurface water far below Hump Creek.

Streams lying east of Hump Creek (Whistle Creek, etc.), do not gain significant quantities of water from springs, but neither do they lose much to subsurface flow, and hence they should produce vastly greater quantities of surface runoff per square mile than do Hump Creek, Work Creek, etc.

The foregoing discussion shows that geologic interpretation by means of aerial photographs provides extremely significant information regarding streamflow at Hump Creek and adjacent basins. A stream like Hump Crek could use a much smaller culvert, for example, than Whistle Creek, even though the two drainages are adjacent to each other, are nearly the same size, are at nearly the same elevation, and have numerous characteristics of similarity.

Similar analyses would seem to be appropriate in the future as part of the hydrologic investigation of any watershed.

CHAPTER XII

CONCLUSIONS AND RECOMMENDATIONS

The research reported in the preceding chapters was conducted in numerous phases, and the conclusions reached cannot easily be condensed into a short space. The very brief statement of conclusions which follows should be supplemented by reference to the various chapters.

1. Precipitation data from Montana stations having long periods of record may be used in a prediction formula to obtain estimates of peak discharges having a 50-year return period. The relationship which was derived, called the peak rainfall frequency-peak flow frequency method, should be refined by extension to other return periods, and it should be checked by testing against data from watersheds in other parts of the country. In its present form use of the method should be limited to furnishing cross checks against peak discharges predicted from other methods.

2. A multiple-regression equation which was developed for five Project watersheds may be used to predict peak discharge and runnoff volume for certain rain or snow caused events. The peak discharge obtained has a unknown return frequency. The equation has not been tried on other watersheds, and its reliability is not known. Future studies of the hydrology of small watersheds for the purpose of making peak flow predictions should concentrate on the determination of watershed characteristics and collection of meteorological data as suggested in this report. Some characteristics and certain types of data seem to have little bearing on peak discharges or runoff volumes.

3. The Soil Conservation Service method may be used to determine runoff volume, and to generate a predicted hydrograph from a hypothesized rainstorm or from a historical event. The runoff volume and hydrograph obtained have unknown return frequencies. When historical data are available, adjustments may be made in watershed characteristics, thereby producing a runoff volume which matches the recorded runoff volume. The reliability of the hydrograph peak generated, however, is doubtful.

4. Of several multiple regression formulas which were tested (some being essentially extensions of the rational runoff method) none were found which could be used with much reliability to predict peak flows having a 50-year return frequency interval on the Project Watersheds. Included in this group are the Boner, Boner-Omang, Potter, and Northern Pacific formulas.

5. Of several stochastic relationships which have been advanced, the Extreme Value (Gumbel) and Log-Pearson Type III methods gave the best results when applied to five Project watersheds. Neither of these methods gave the best results consistently.

6. Certain areas of Montana have been found to apparently be hydrologically homogeneous. Within these areas streamflow data from two or more watersheds may be pooled to produce a single record which is longer than that from any of the individual records. To obtain maximum benefits from the current Small Drainage Program, some of the gaging stations which are presently located within these areas might now be relocated in sections of the state where no streamflow records are now being collected.

7. The length of runoff record has a very significant bearing on the reliability of peak flows predicted by stochastic methods for high return frequency intervals. At the 50-year return frequency interval, as much as 50 percent difference in the predicted discharge was noted when using 33 years of record as opposed to 16.

Recommendations are as follows:

1. The most reliable estimates of peak discharges at the 50-year return frequency interval may be made at the present time by the use of stochastic methods, notably the Gumbel and the Log-Pearson Type III methods. If an estimate of the 50-year peak flow is required from a watershed where no streamflow records are available, the following procedure is recommended:

a) Use the Gumbel and/or Log Pearson Type III method on several nearby gaged watersheds and determine for each the ratio of the 50-year peak discharge to the mean annual peak discharge or the ratio of the 50-year peak discharge to the 10-year peak discharge.

b) Use a multiple regression method such as the Boner or Boner-Omang equation to obtain an estimate of the mean annual peak discharge or the 10-year peak discharge for the ungaged watershed.

c) Use the average of the ratios obtained in step a) as a factor to be multiplied by the mean annual peak discharge or the 10-year peak discharge obtained in step b), and thereby obtain an estimate of the 50-year peak discharge at the ungaged watershed.

d) Use independent methods, such as the peak rainfall frequency-peak flow frequency method developed in this report, to check the peak flow obtained in step c). If major disagreement exists, caution must be used in applying the estimated peak discharge to design situations.

2. Additional study of the factors involved in the peak rainfall frequency-peak flow frequency method is needed to perfect this method and improve its reliability.

3. More reliable estimates of peak flow magnitudes at high return frequency intervals can be made only as longer historical records of streamflow from small Montana watersheds become available. Records as long as 30 years must be obtained in some areas of the state before much confidence can be placed in estimates of 50-year peak flows. There are, however, several areas of the state where the density of gaging stations can now be reduced. The gaging stations thus released should be relocated in areas of the state where no records are presently available.

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